

What Have we Learnt From Jets at the LHC

Nima Zardoshti

CERN

Why Study Jets in Heavy-Ion Collisions?

- One of the primary methods of understanding the QGP is to probe partonic energy loss
- Partons lose energy both incoherently and coherently whilst traversing the medium
 - Need to consider the shower collectively
- Modifications to the parton shower in Heavy-Ion collisions characterise this energy loss
- Jets are the best experimental proxy for the original scattered partons:
 - Study the kinematics of the partons – Jets as extended objects
 - Study the structure of the shower – Jet substructure (see Yi-Chen's talk next)
- Through jet-medium interactions we can infer some of the fundamental properties of the medium

Jets Probe all Scales of the Medium

❖ Jets are a multi-scale problem : Forces us to consider a wide range of QCD phenomena

Hard Processes

Calculable in pQCD

Medium induced gluon radiation

Collisional energy loss

Moliere scattering

Vacuum DGLAP evolution

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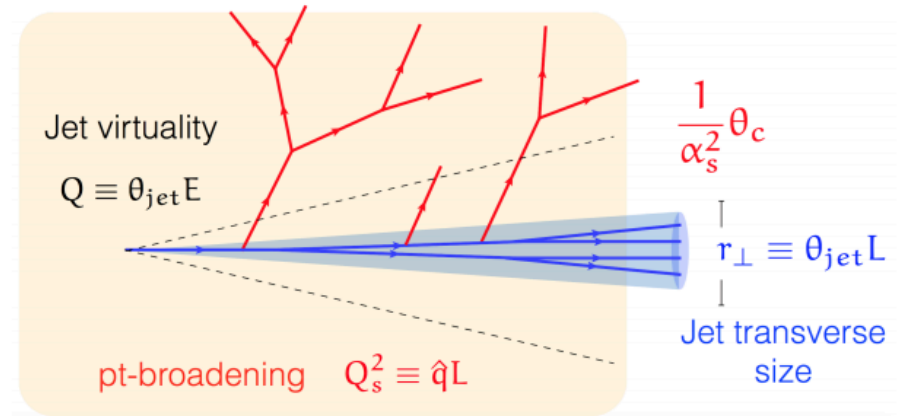
Soft Processes

Experimentally constrained + Lattice QCD

Soft uncorrelated background in the jet cone

Wake left behind by traversing jet

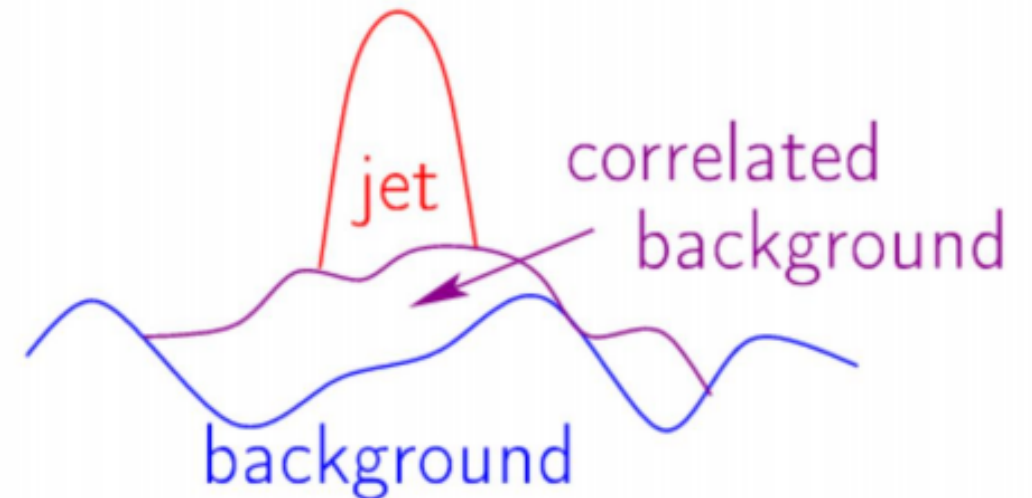
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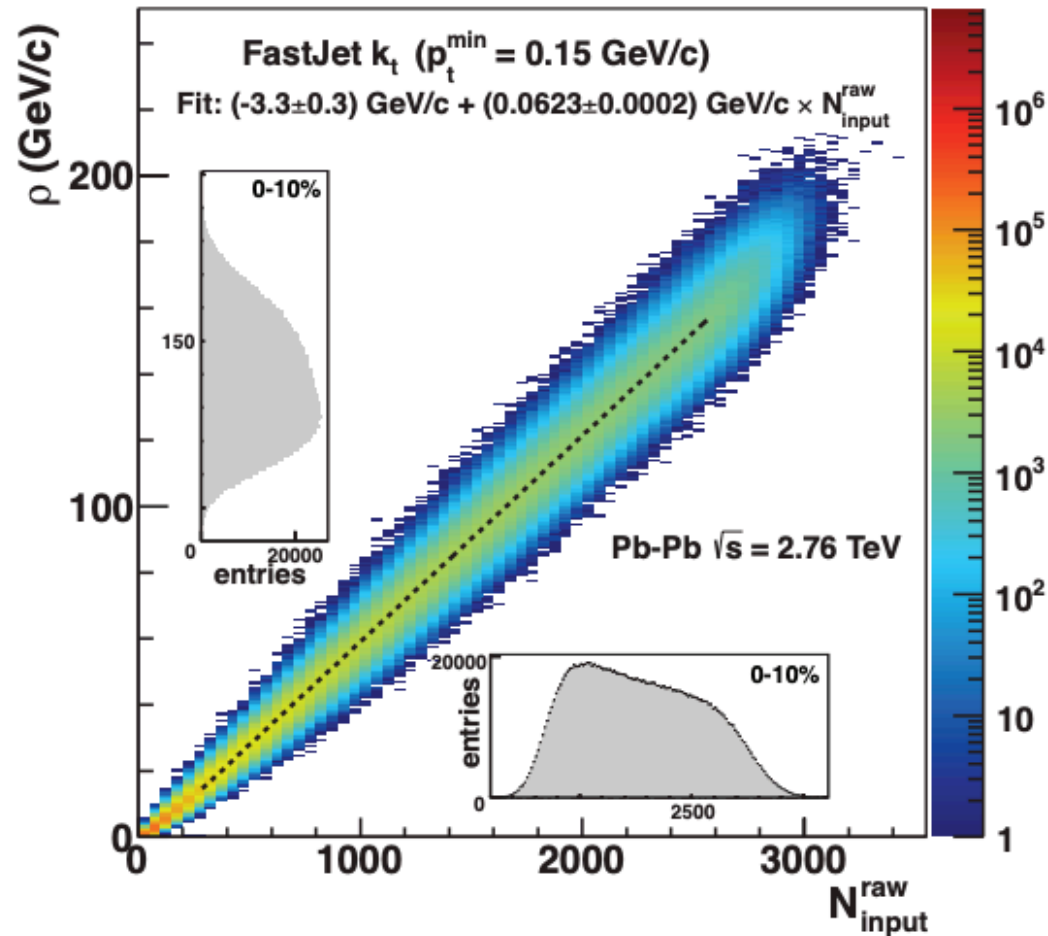
What Ends Up Inside the Jet Cone?

The phase space inside a jet cone is populated by three main components:

- The jet signal : these are constituents directly emerging from the fragmenting parton
- The uncorrelated background : constituents arising from (mostly soft) processes decoupled from the jet
- The medium response: energy flow which did not originate from the scattered parton, but which is a result of the parton traversing through the medium
- ❖ How do we separate these and what are we interested in?



How to Deal with the Uncorrelated Background?



Event-by-event corrections to remove the average background contribution per jet

- Iterative noise/pedestal subtraction
- Area-based subtraction
- Constituent subtraction
- Derivatives subtraction
- ...

Fluctuations of the background remain in the jet cone

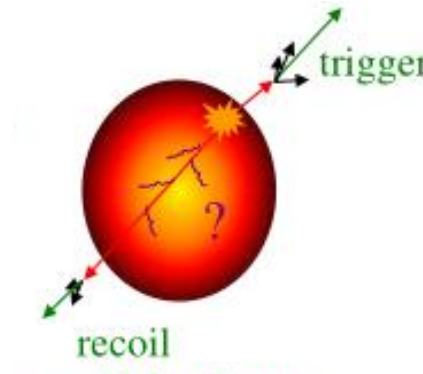
- Can be **corrected** for using unfolding
- Or **accounted** for using smeared or embedded MC samples

How to Remove Combinatorial Jets?

- ❖ Combinatorial jets are fluctuations of the background which are indistinguishable from hard-scatter jets
- ❖ Dominant at low $p_{T,\text{Jet}}$ and large jet radii

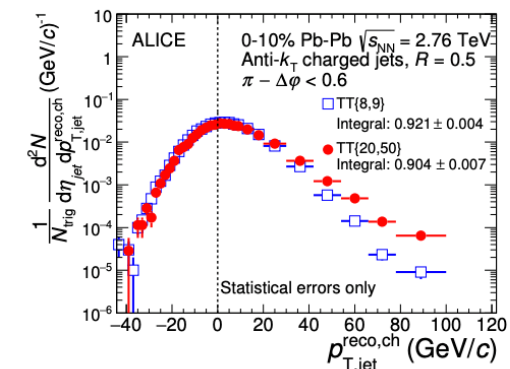
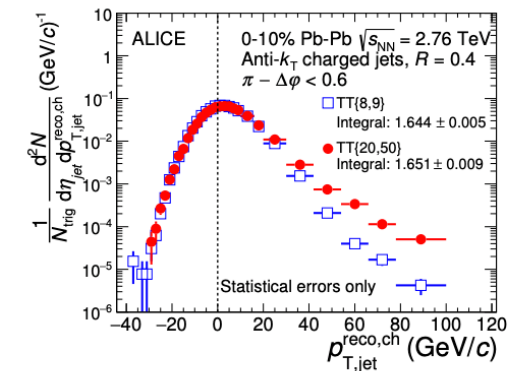
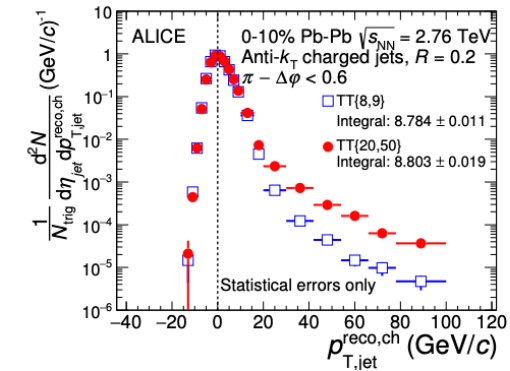
To remove:

- ❖ Make measurements at high $p_{T,\text{Jet}}$
- ❖ Tag back-to-back jets
- ❖ Use event-average methods such as h-jet coincidence



H-jet coincidence technique:

- ❖ Define two high p_T trigger hadron classes
- ❖ Measure yield of jets recoiling from trigger hadrons
- ❖ Expected that the contribution of combinatorial jets is equal in both classes
- ❖ Subtract the per trigger normalised yields



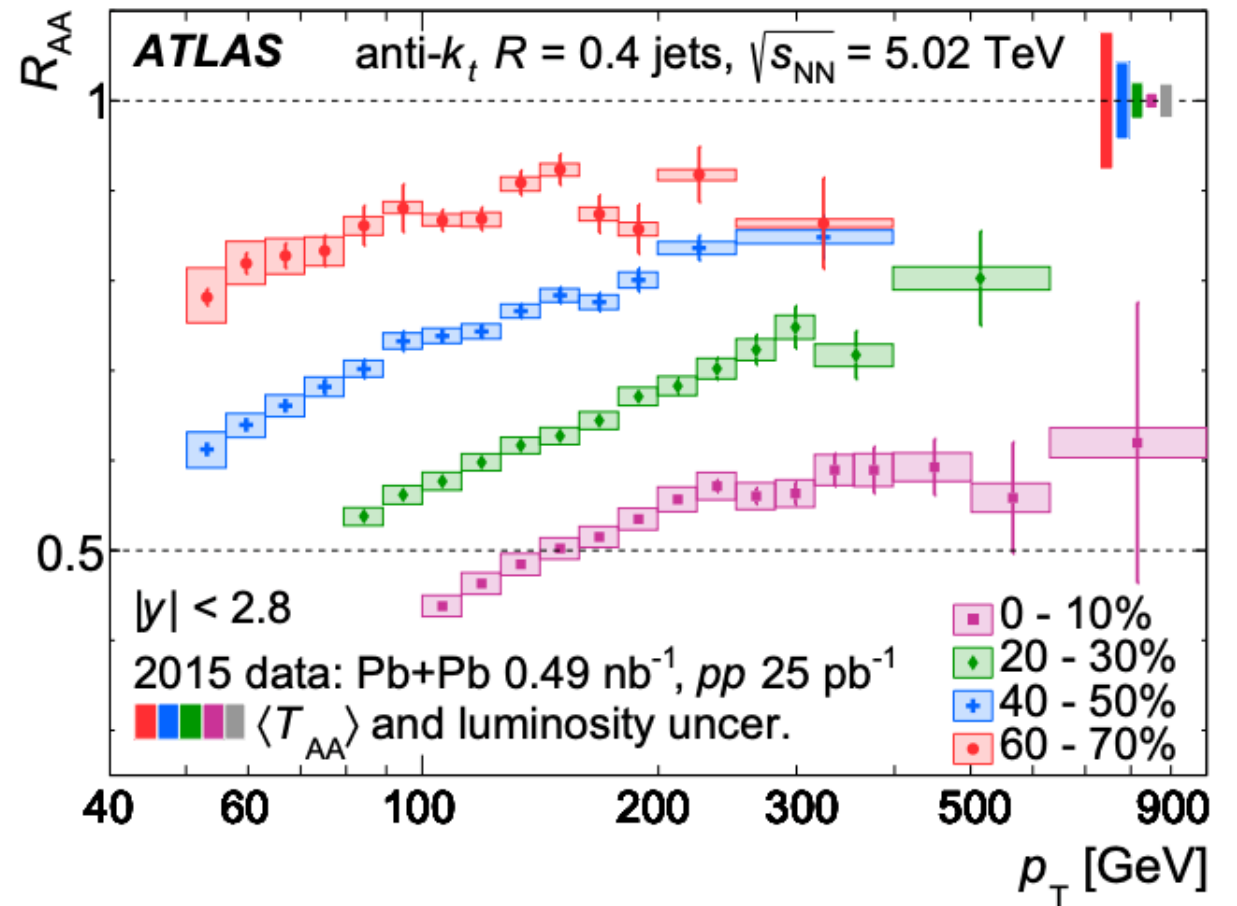
Signal for Jet Quenching

- Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \left. \frac{d^2 N_{\text{jet}}}{dp_T dy} \right|_{\text{cent}}}{\langle T_{AA} \rangle \left. \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \right|_{pp}},$$

- A direct observable to measure jet quenching
- Jets are heavily suppressed in central collisions
- Jets suppression still seen in peripheral collisions, indicating that a (smaller) medium is formed

Which energy loss dependencies can we probe?



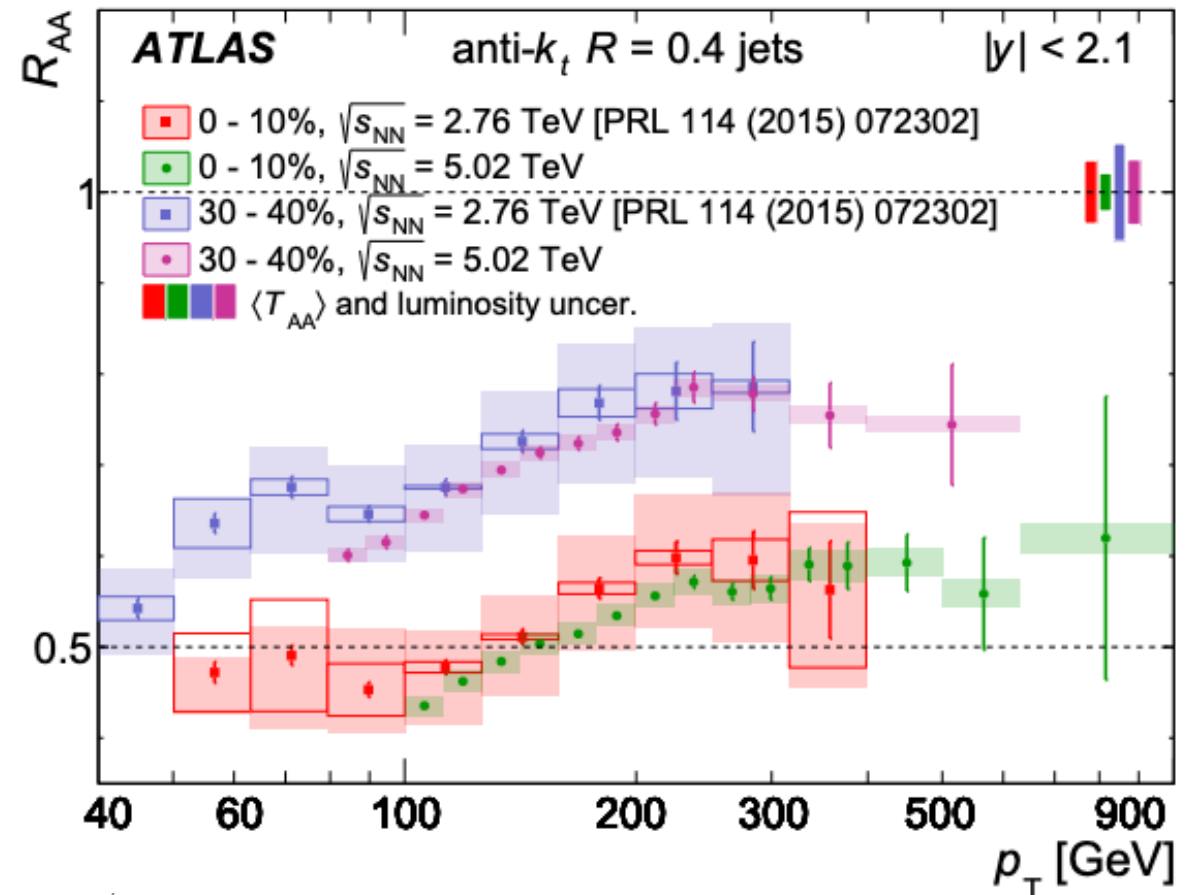
Collision Energy Dependence

- Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \left. \frac{d^2 N_{\text{jet}}}{dp_T dy} \right|_{\text{cent}}}{\langle T_{AA} \rangle \left. \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \right|_{pp}},$$

- A direct observable to measure jet quenching
- Jets are heavily suppressed in central collisions
- Jets suppression still seen in peripheral collisions, indicating that a (smaller) medium is formed

- No dependence on collision energy observed
- Can be explained by the hardening of the $p_{T,\text{Jet}}$ spectrum at higher collision energies

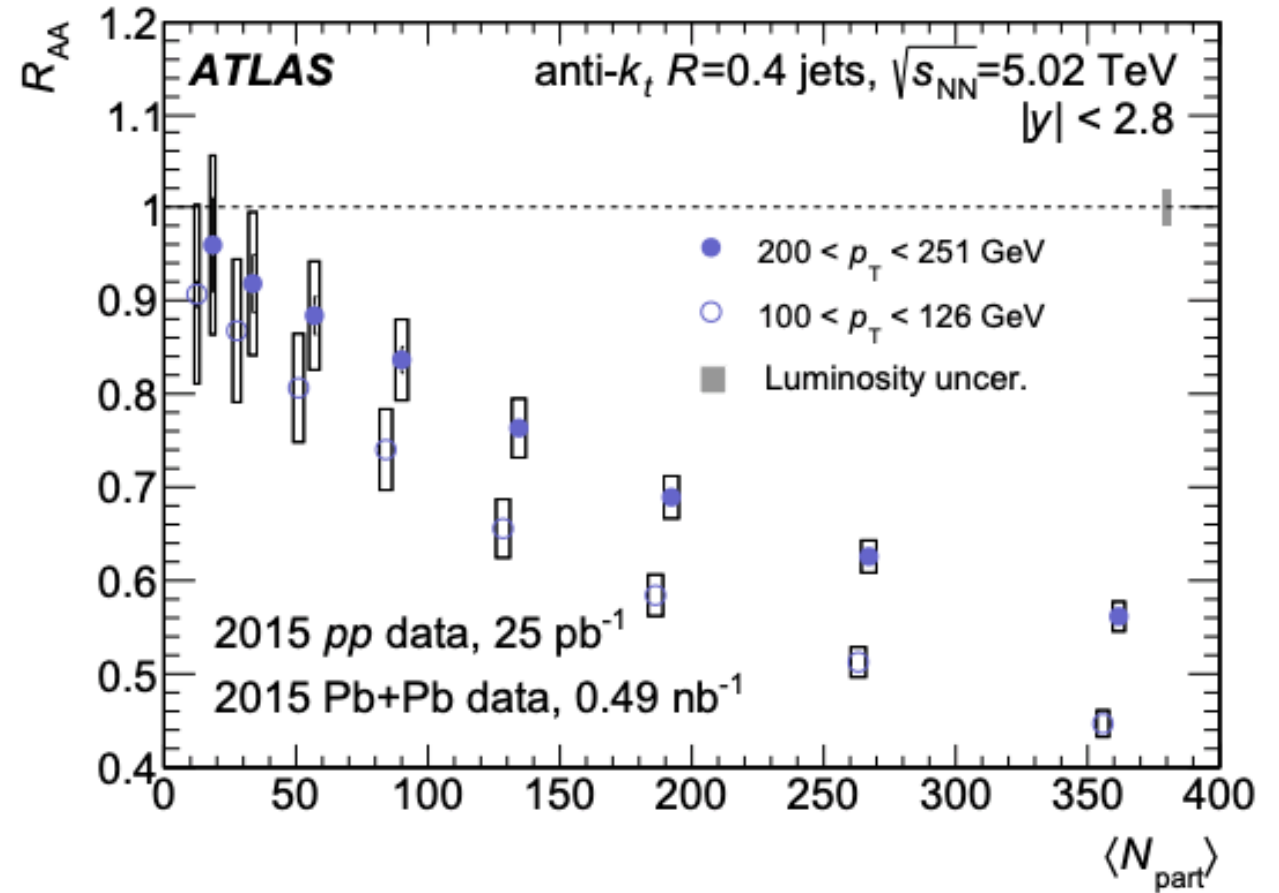


$p_{T,\text{Jet}}$ Dependence

- Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \left. \frac{d^2 N_{\text{jet}}}{dp_T dy} \right|_{\text{cent}}}{\langle T_{AA} \rangle \left. \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \right|_{pp}},$$

- A direct observable to measure jet quenching
- Jets are heavily suppressed in central collisions
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Higher $p_{T,\text{Jet}}$ appear less suppressed

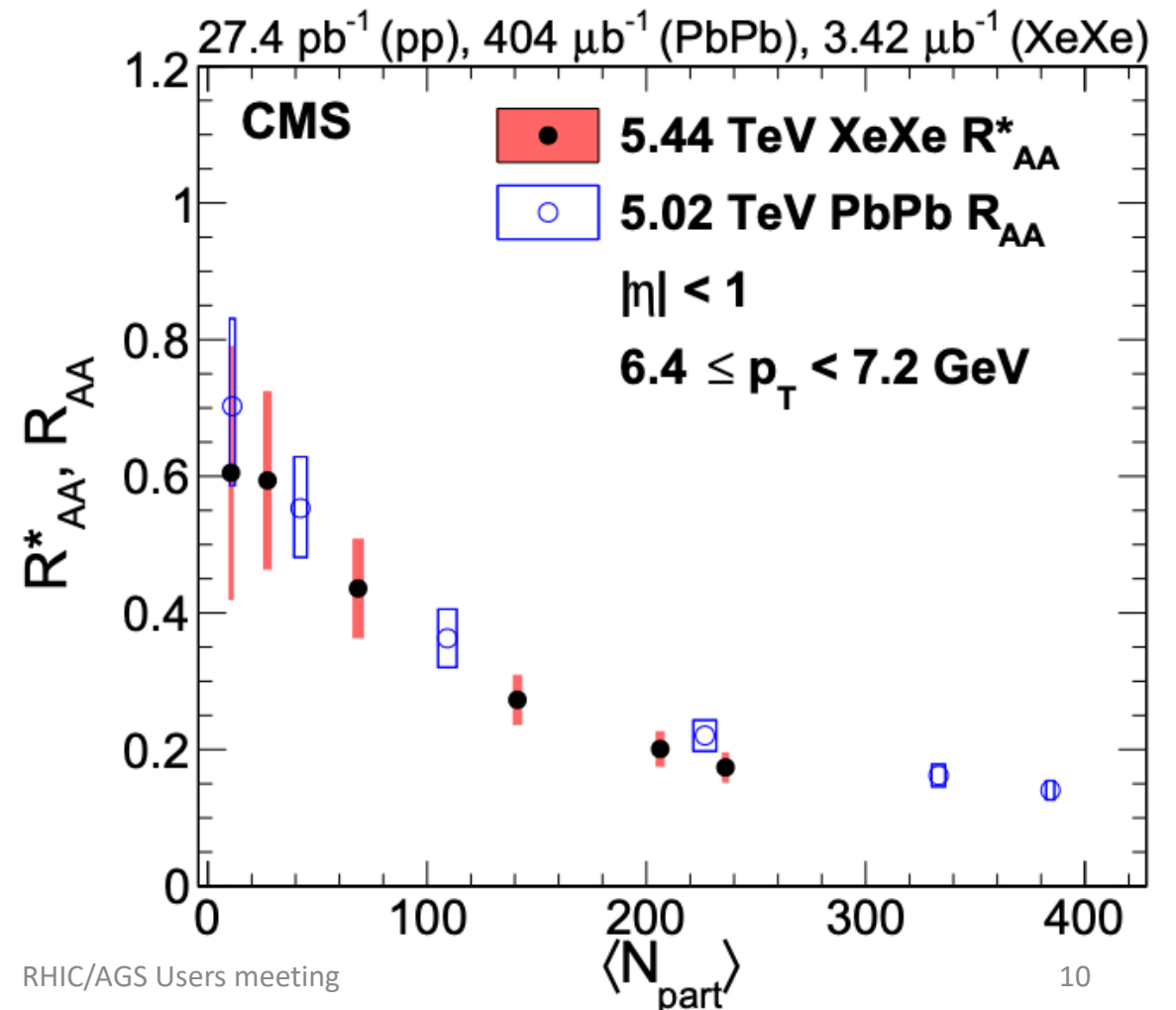
Initial State Dependence

- Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{jet}}}{dp_T dy} \Big|_{\text{cent}}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \Big|_{pp}},$$

- Xe-Xe collisions are expected to have smaller initial state effects
- Due to differing nuclear sizes, the number of participants is not equal in a given centrality bin for Xe-Xe and Pb-Pb
- Energy loss as a function of the number of participants is consistent between two systems

Not a jet measurement

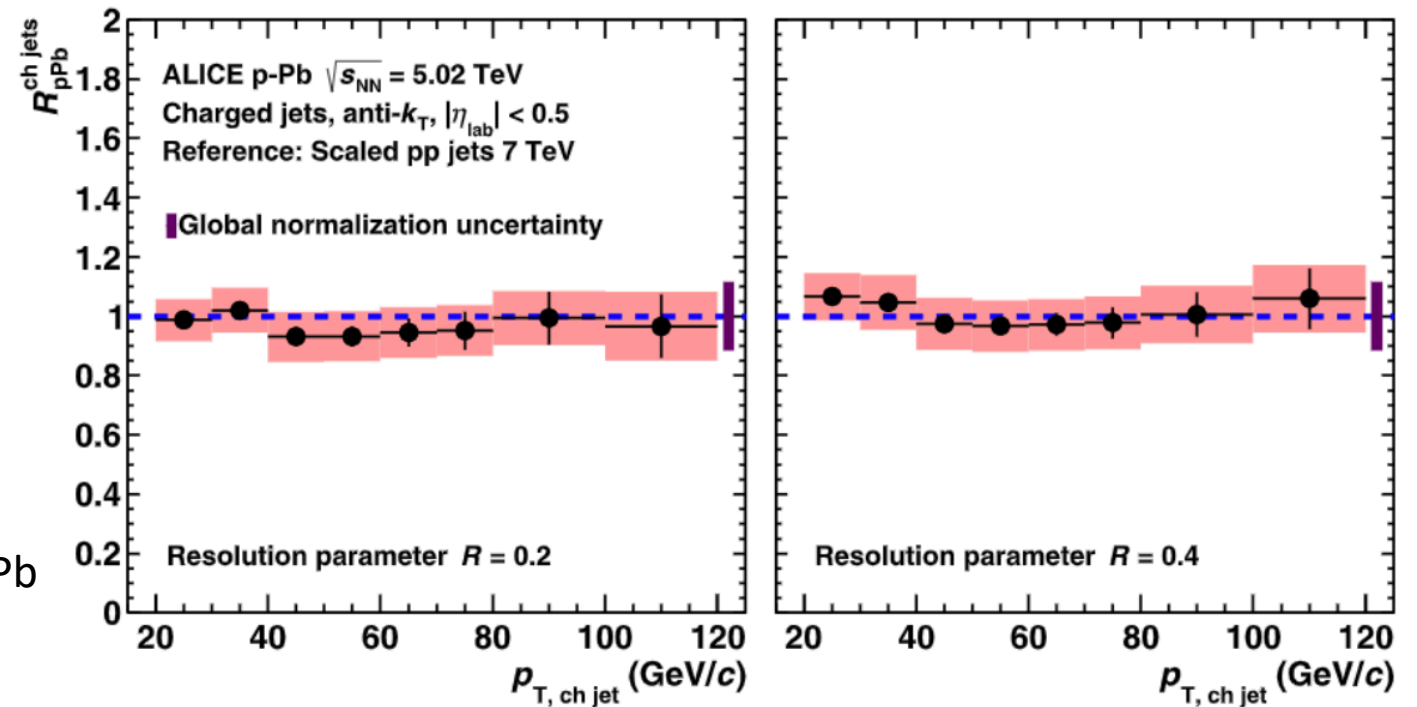


System Size Dependence

- Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{jet}}}{dp_T dy} \Big|_{\text{cent}}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \Big|_{pp}},$$

- Small systems such as p-Pb and high multiplicity pp show signs of collective behavior
- However no jet quenching is observed in p-Pb

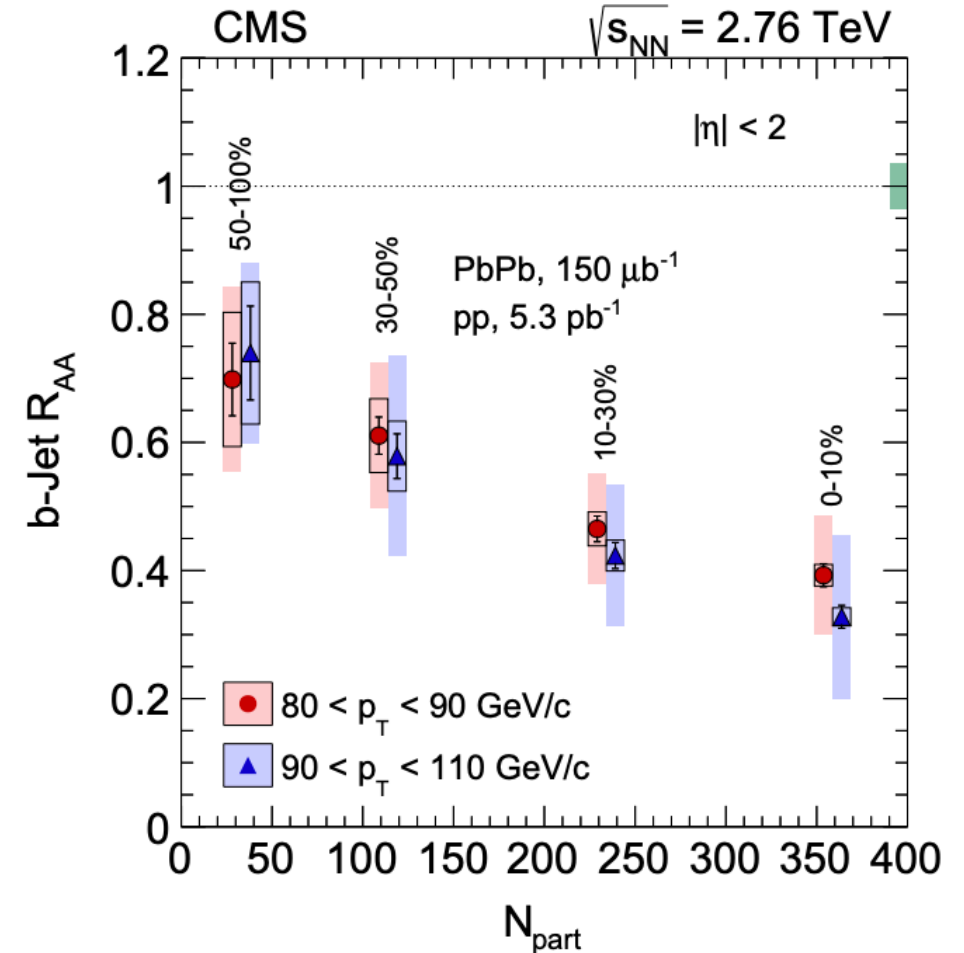


Flavour Dependence

- Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{evt}} \frac{d^2 N_{jet}}{dp_T dy} \Big|_{cent}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{jet}}{dp_T dy} \Big|_{pp}},$$

- Quark jets are expected to lose less energy than gluon jets
- Heavy flavour partons are expected to lose less energy than light flavour partons
 - ❖ Radiation suppressed in the quark's direction of motion – proportional to mass
- Would a strongly coupled QGP have mass effects for energy loss? (Ads/CFT)



b-Jet energy loss found to be qualitatively consistent with that of inclusive jets

Rapidity Dependence

➤ Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \left. \frac{d^2 N_{\text{jet}}}{dp_T dy} \right|_{\text{cent}}}{\langle T_{AA} \rangle \left. \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \right|_{pp}},$$

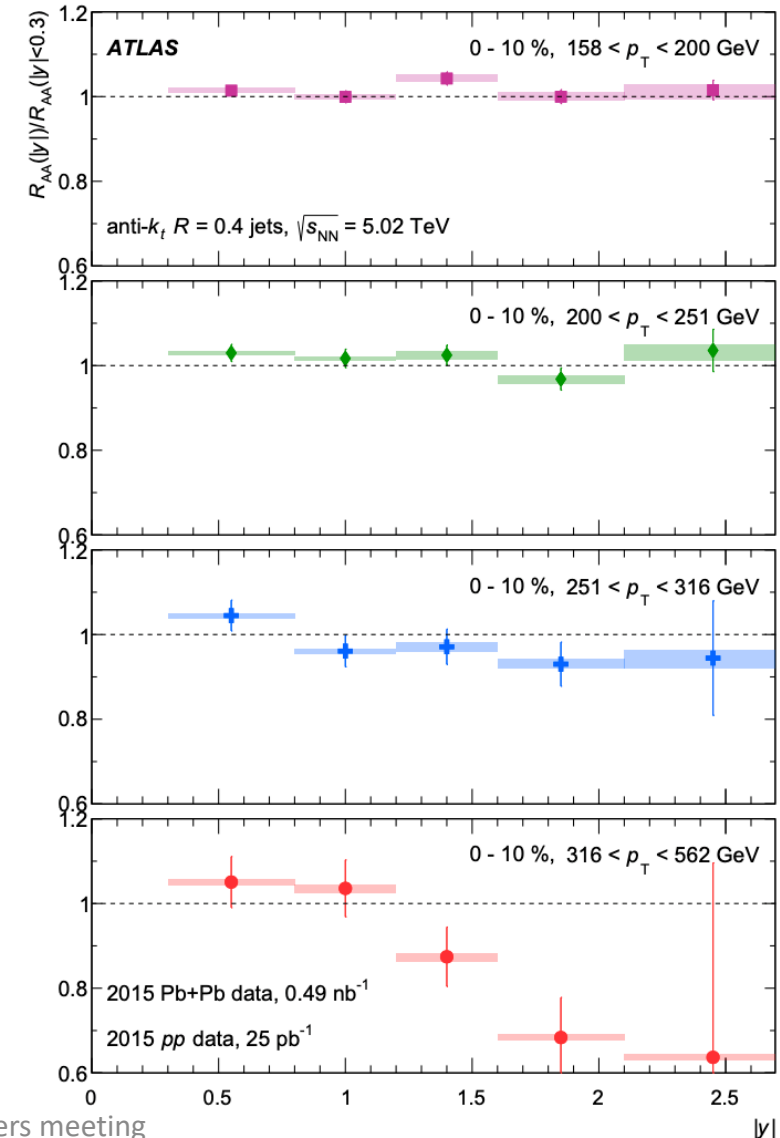
➤ Varying the rapidity changes the quark gluon fraction

- ❖ Increased quark fraction at large rapidity

➤ Larger suppression observed at large rapidities for the highest $p_{T,\text{Jet}}$ intervals

Can be explained by:

- ❖ the steepening of the $p_{T,\text{Jet}}$ spectra in the forward rapidity region
- ❖ $p_{T,\text{Jet}}$ dependence of quark jet fraction

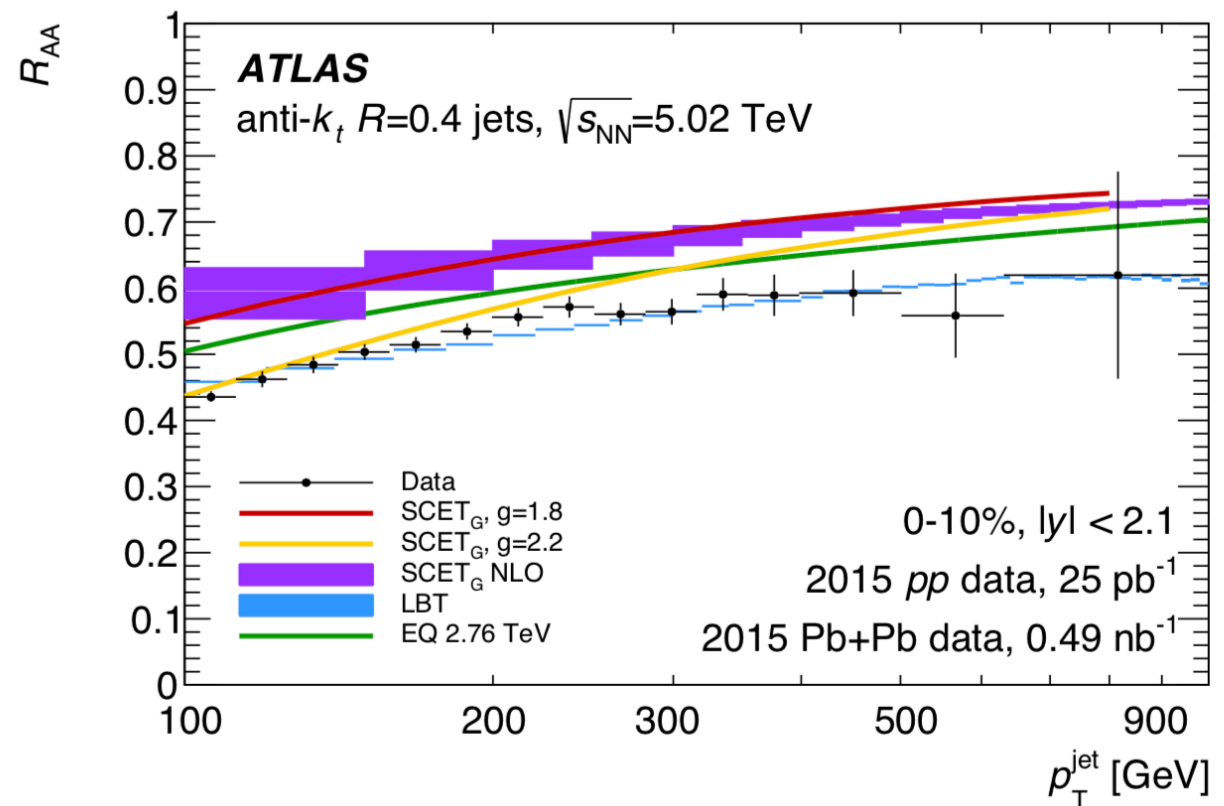


Theory comparisons

➤ Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{jet}}}{dp_T dy} \Big|_{\text{cent}}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \Big|_{pp}},$$

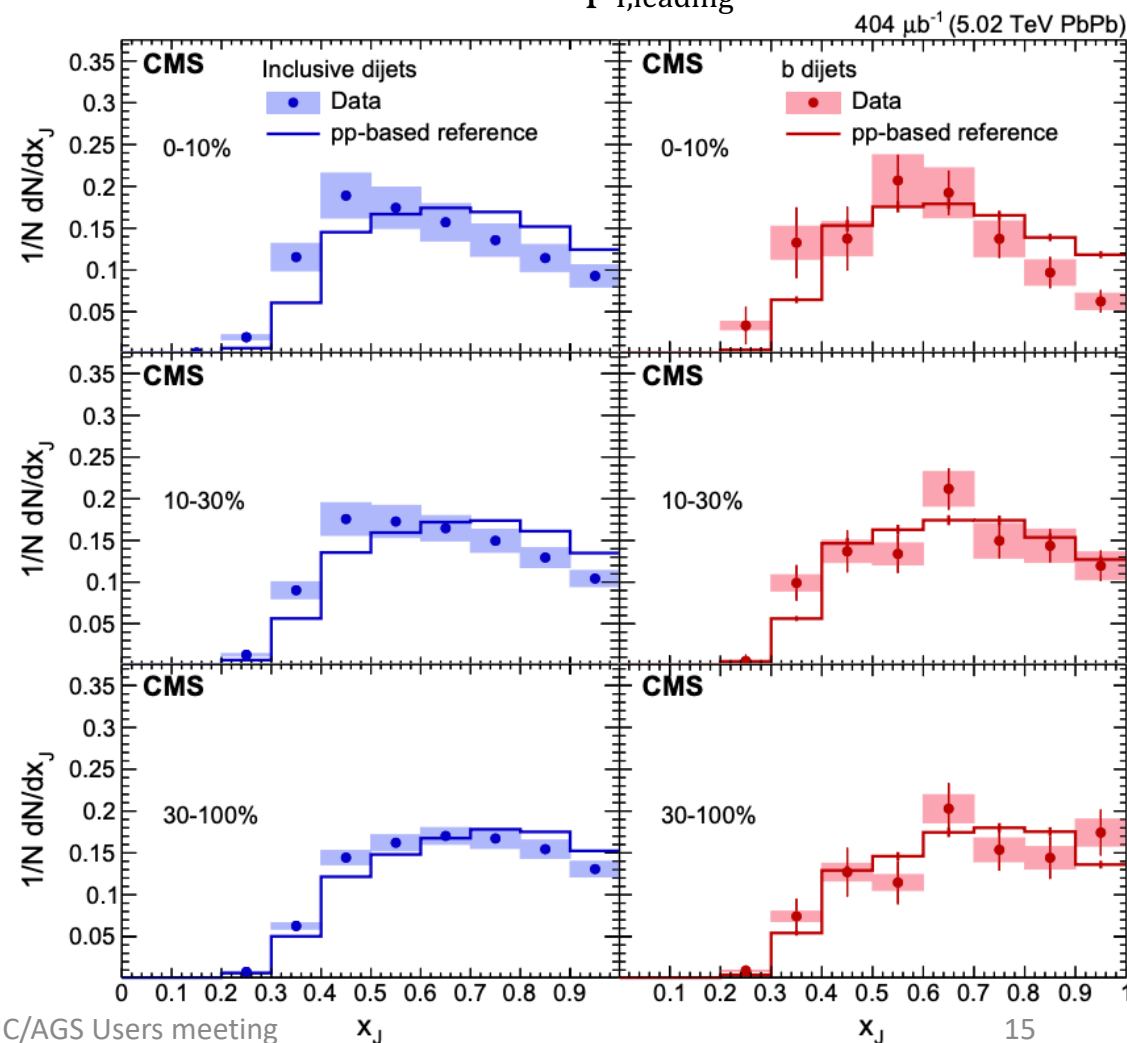
- All models reproduce the trends seen in data
- $p_{T,\text{Jet}} < 250 \text{ GeV}/c$ best described by SCET_G $g=2.2$
- $p_{T,\text{Jet}} > 250 \text{ GeV}/c$ best described by LBT
- Note that the EQ model is parametrised based on energy loss at a lower collisional energy



Probing the Pathlength Dependence of Energy Loss

- The momentum imbalance of dijets is sensitive to the different in-medium pathlengths traversed
- The imbalance increases with increasing centrality
- Tagging the initiating parton can give evidence for the flavour dependence of quenching
- b-dijets provide a quark jet sample and suppress gluon splitting

$$x_J = \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}}}$$

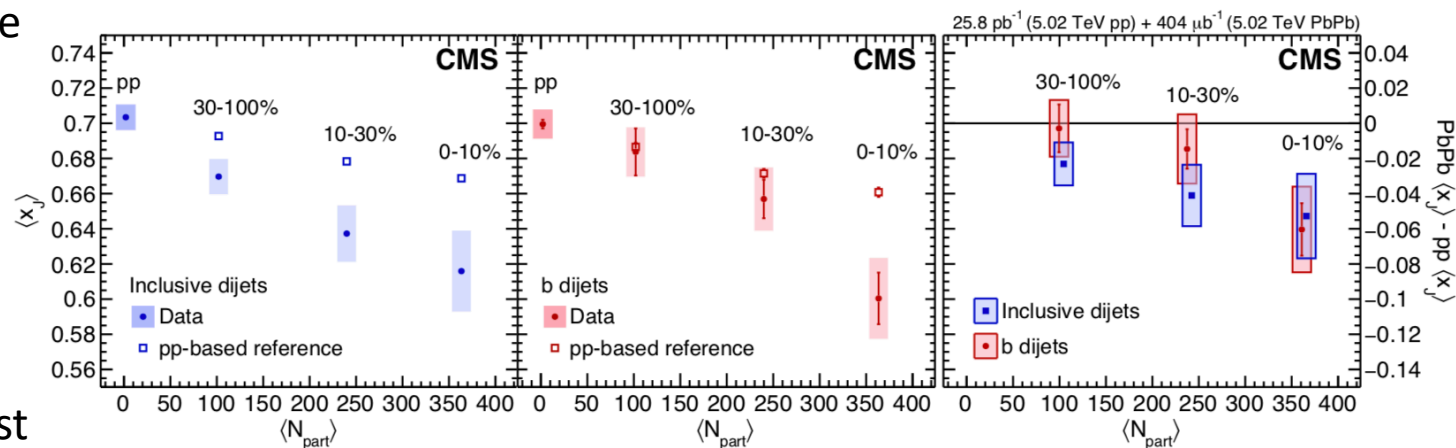


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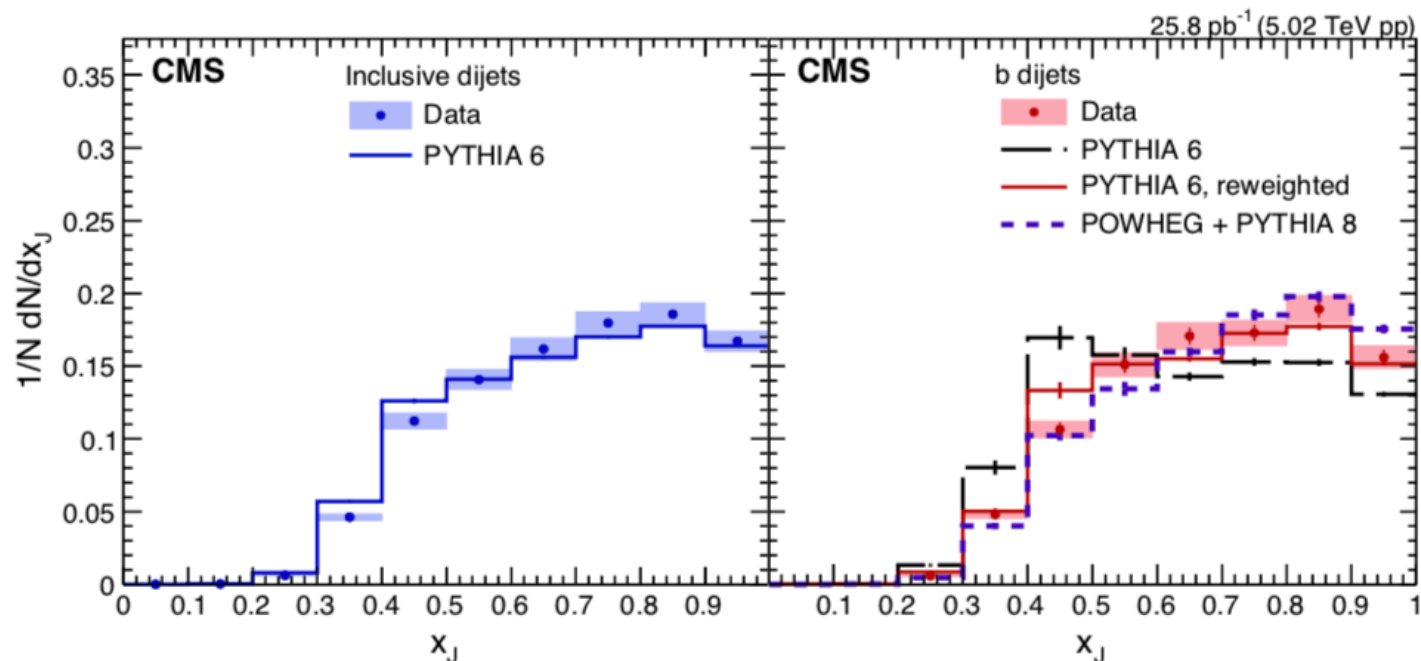
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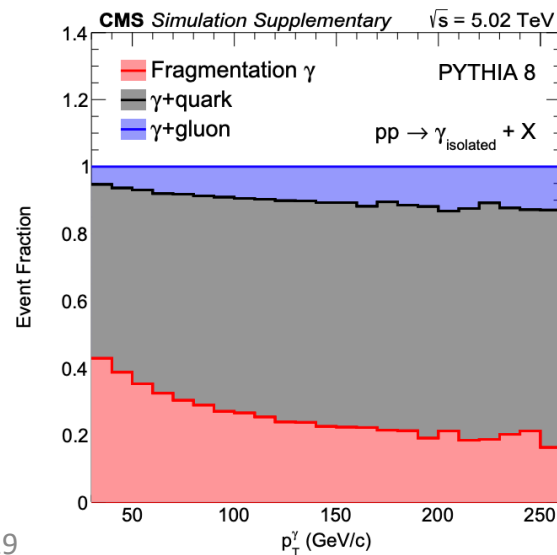
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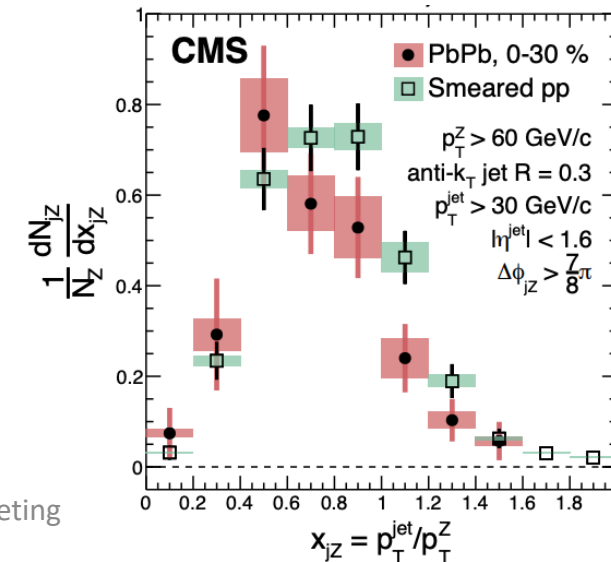
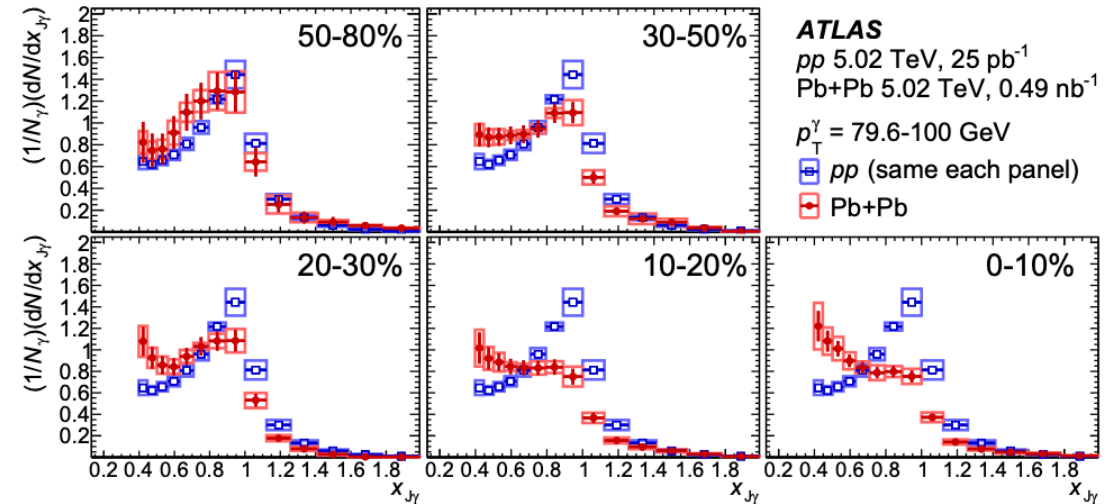
- ❖ Comparison of pp results to models shows importance of next-to-leading order effects for b-dijet imbalance
- ❖ Important to consider when comparing to models in Pb-Pb

Momentum Imbalance for Boson-Jet Pairs

- Colourless bosons are unquenched in the medium
- Provide an accurate reference for the jet's original energy
- Photon and z-boson tagged jets are more likely to originate from quarks

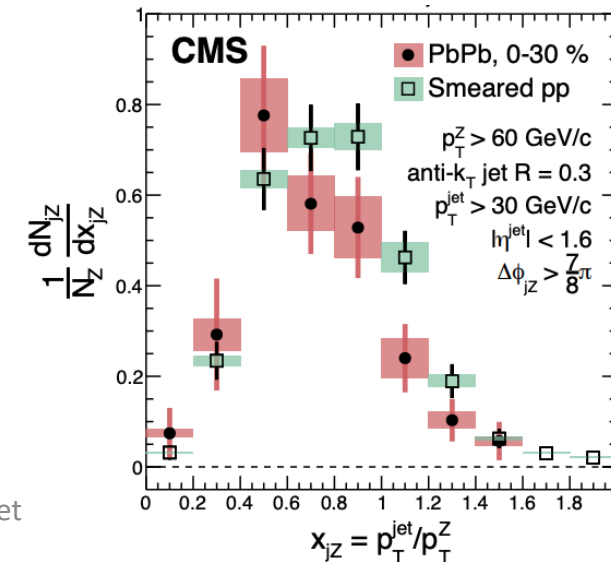
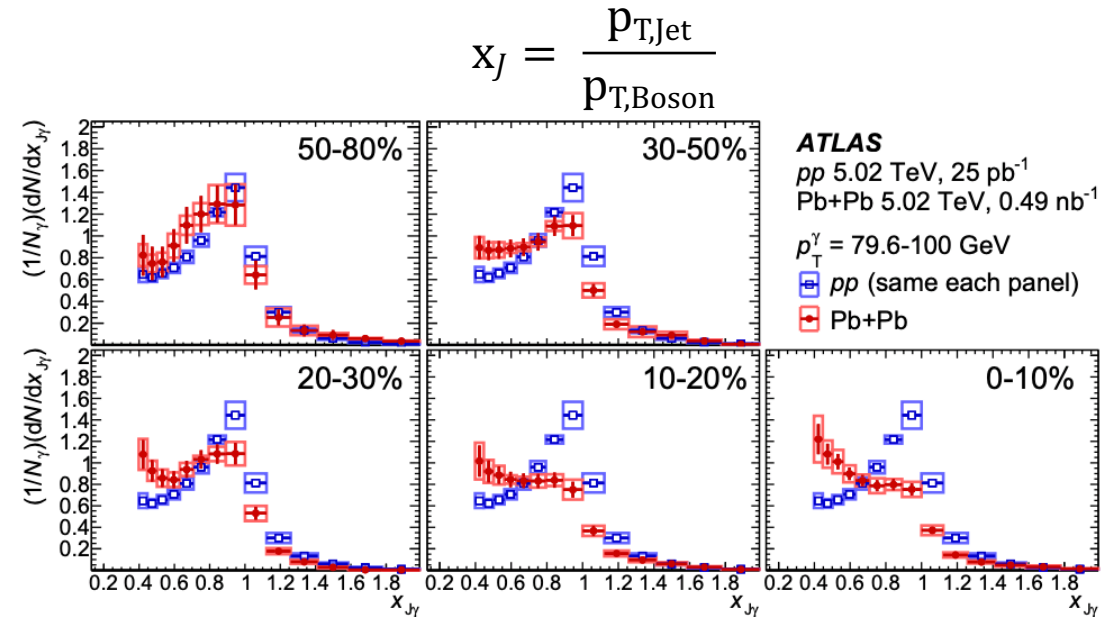


$$x_J = \frac{p_{T,\text{Jet}}}{p_{T,\text{Boson}}}$$



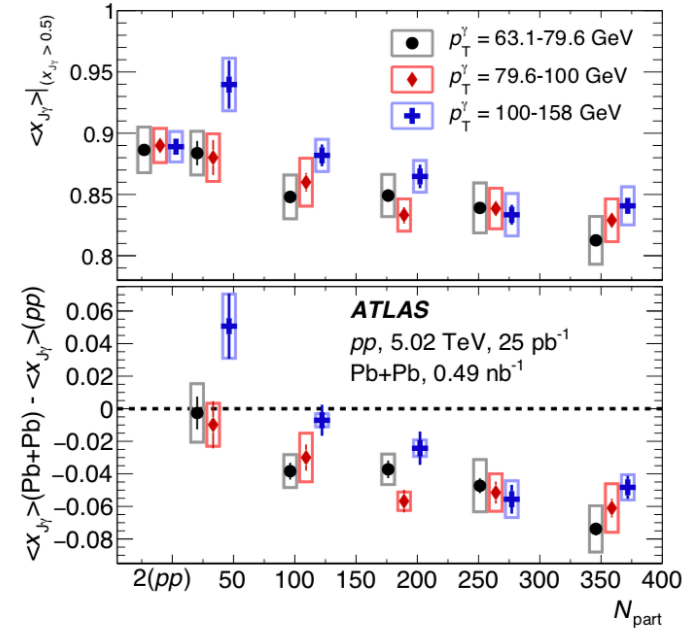
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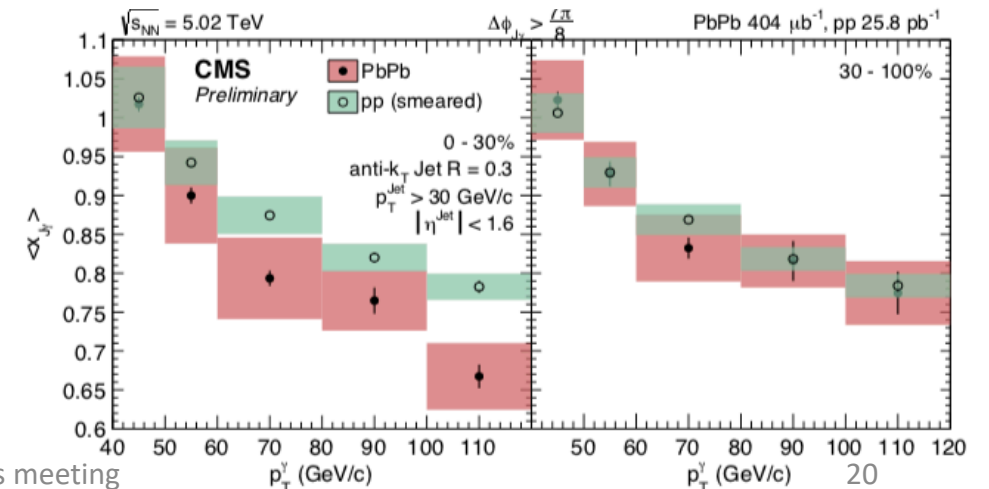


Momentum Imbalance for Boson-Jet Pairs

- Colourless bosons are unquenched in the medium
- Provide an accurate reference for the Jet's original energy
- Photon and z-boson tagged jets are more likely to originate from quarks
- The momentum imbalance shifts significantly with increased collision centrality
- This can be seen more clearly by taking the averages of the distributions



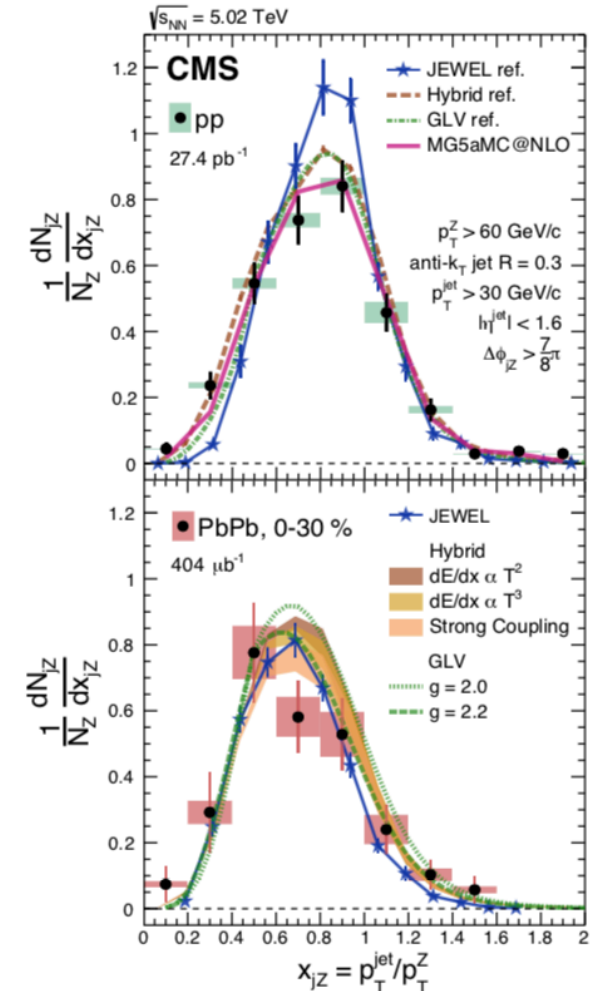
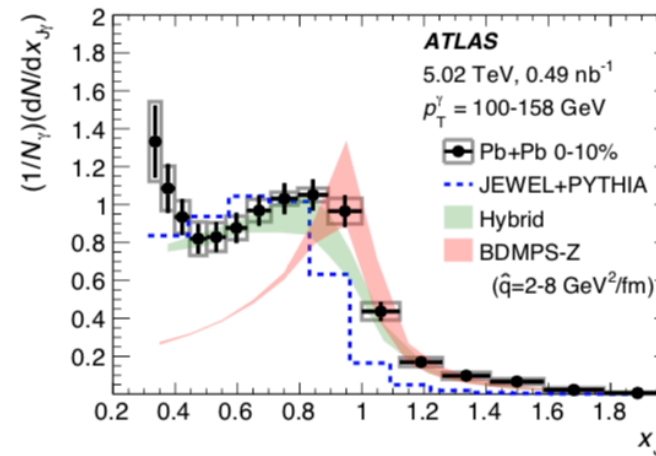
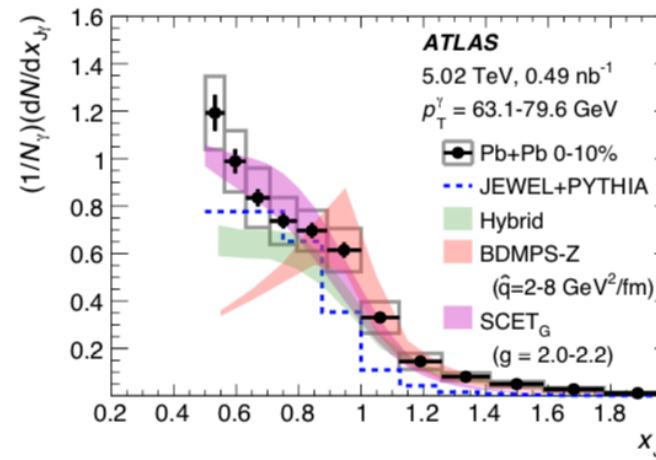
$$x_J = \frac{p_{T,Jet}}{p_{T,Boson}}$$



Model Comparisons

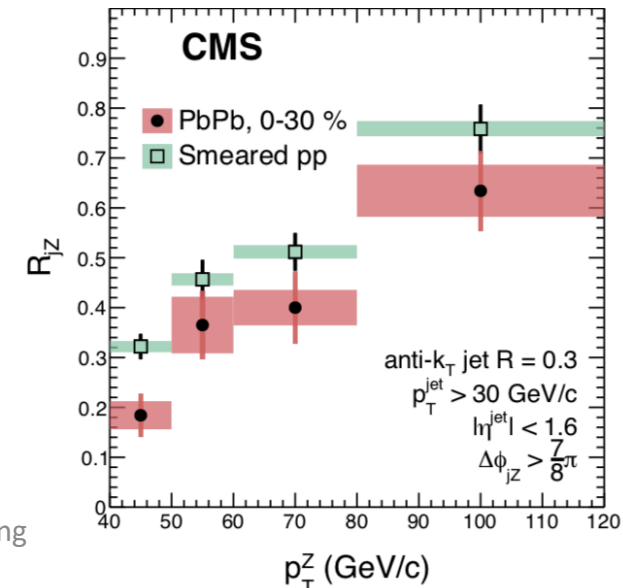
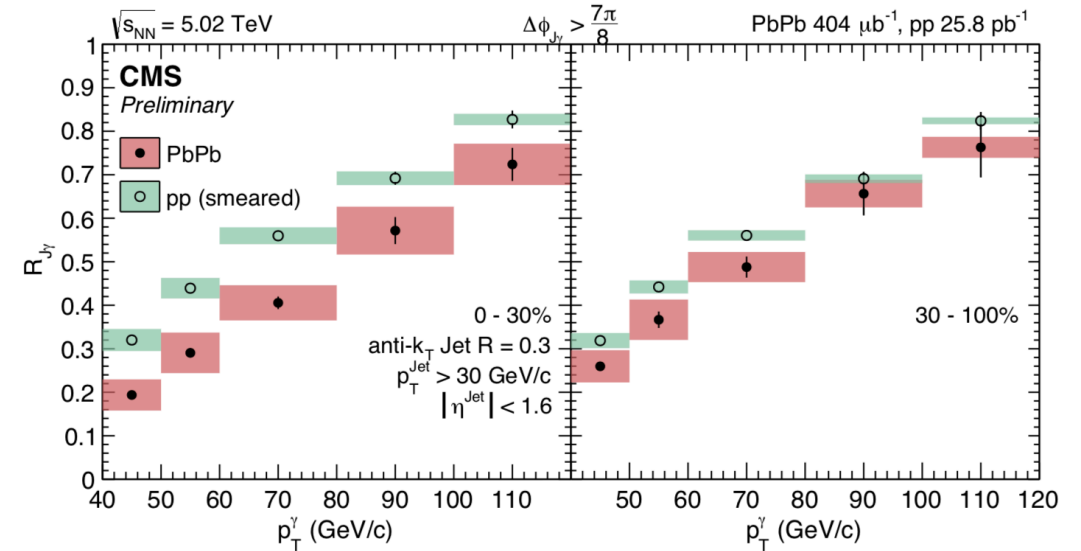
$$x_J = \frac{p_{T,\text{Jet}}}{p_{T,\text{Boson}}}$$

- ❖ For photon tagged jets the data driven models are in better agreement than those based on perturbative calculations
- ❖ The increase in yield at small momentum fractions (< 0.5) is not well described by any model
- ❖ For the z-boson tagged jets, all models other than JEWEL describe the pp data well
- ❖ For the Pb-Pb results, all models including JEWEL are within reasonable agreement



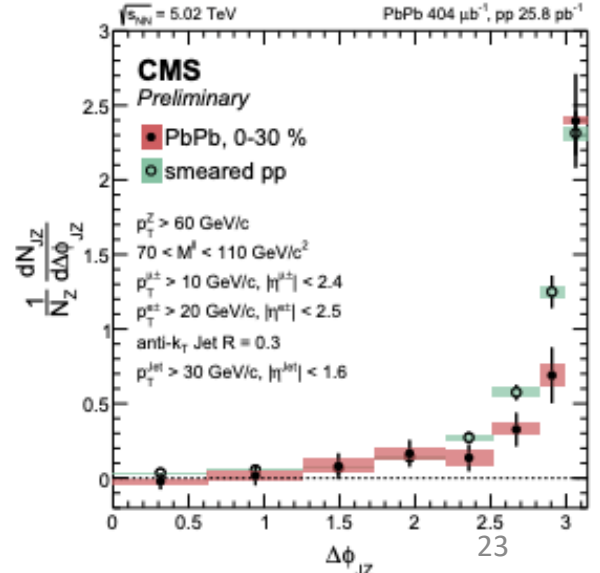
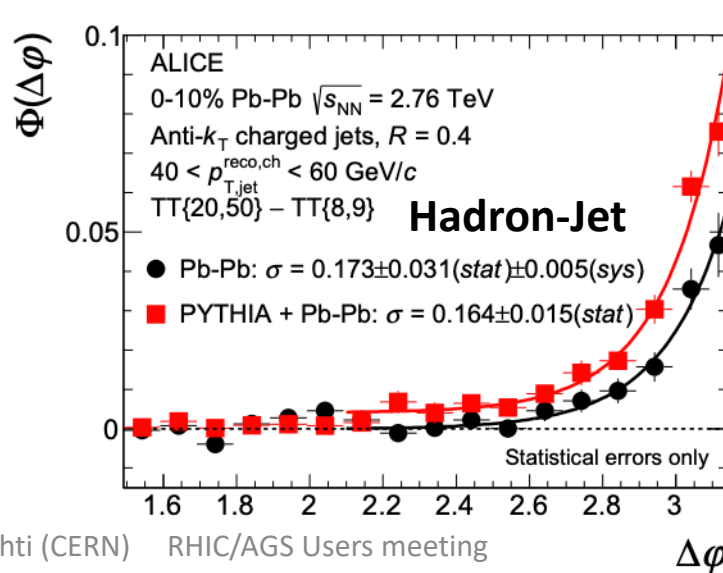
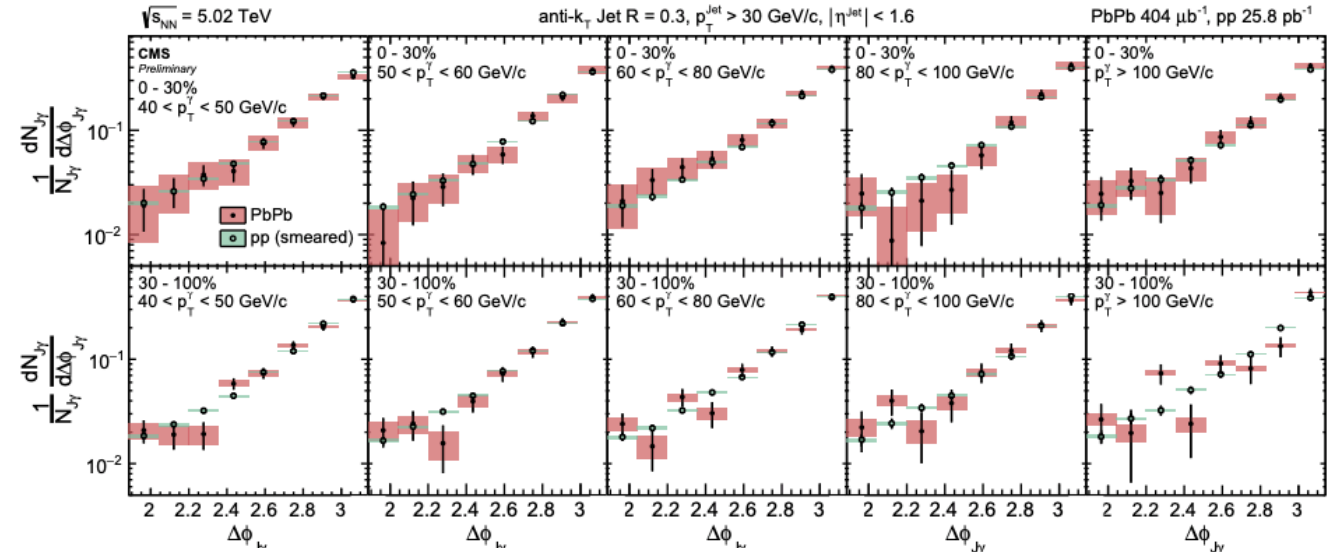
Number of Jets Associated with the Boson - Complementary

- The number of jets associated with both photons and z-bosons are smaller in PbPb than pp
 - ❖ More jets are quenched to below 30 GeV/c
- Larger modification observed with increasing centrality
- This number is expected to increase as the $p_{T,Boson}$ increases due to the increased phase-space available for $p_{T,Jet} > 30$ GeV/c
- The difference between Pb-Pb and pp is relatively constant as a function of $p_{T,Boson}$. This indicates that a smaller fraction of jets which start with a large energy are subsequently lost in Pb-Pb



Are the Jets Deflected with Respect to the Boson?

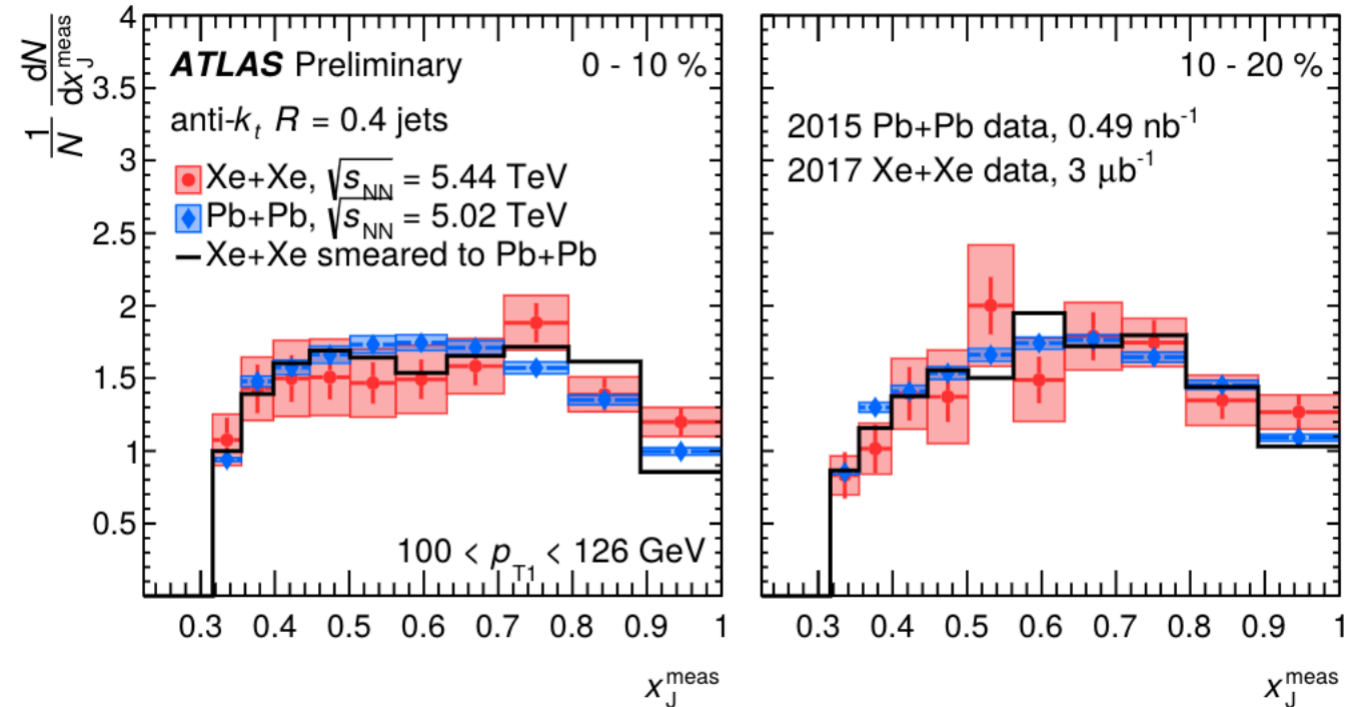
- Interactions with the medium can deflect the jet axis
- This can give information about the medium's degrees of freedom
- Bosons provide an undeflected axis as a reference
- Differences are expected to be more significant at low $p_{T,\text{Jet}}$, as high virtuality jets are Sudakov dominated
- Hadron-jet coincidence technique has the potential to extend measurements to much lower $p_{T,\text{Jet}}$



Momentum Imbalance – New system

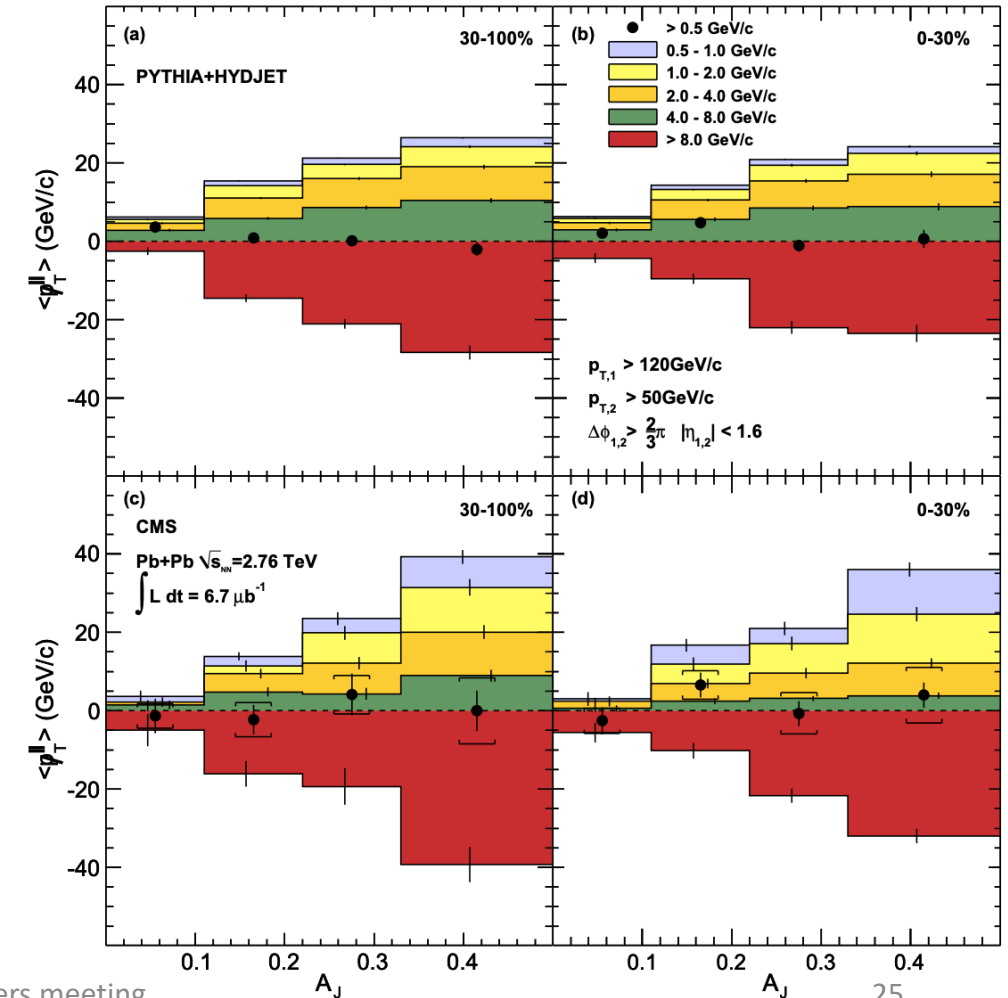
$$x_J = \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}}}$$

- Less quenching expected in Xe-Xe
 - ❖ Less energy density
 - ❖ Smaller pathlength for traversing partons
- No significant differences observed within the same centrality intervals



Where is the Missing Energy?

- How much must we open the jet cone in order to recover the missing energy in a dijet system? $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$ $\not{p}_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}})$
- The missing energy can be recovered by taking into account very soft particles at large rapidities (< 2.4)
- The larger momentum carried by high p_T tracks ($> 8 \text{ GeV}/c$) in the direction of the leading jet is balanced by the combined contribution of softer particles in the direction of the subleading jet
- In data the balancing contribution is mostly dominated by soft particles ($< 4 \text{ GeV}/c$) rather than intermediate (4-8 GeV/c) ones. This effect is enhanced with increasing centrality
- In the MC the intermediate p_T tracks have a much larger balancing contribution, which is relatively unchanged with centrality
- Need to make jet measurements with large jet radii to be sensitive to these effects



How is the Energy Redistributed in the Jet Cone?

- ❖ Jet fragmentation is expected to be modified in heavy-ion collisions
 - Redistribution of energy in/out of the jet cone
 - Change in the jet multiplicity
- ❖ Fragmentation is also sensitive to hadronization effects
- ❖ Gives an indication as to the internal modification of the jet due to quenching

Can be measured longitudinally

$$z \equiv p_T \cos \Delta R / p_T^{\text{jet}}$$

$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dn_{\text{ch}}}{dz},$$

$$R_{D(z)} \equiv \frac{D(z)_{\text{PbPb}}}{D(z)_{pp}}$$

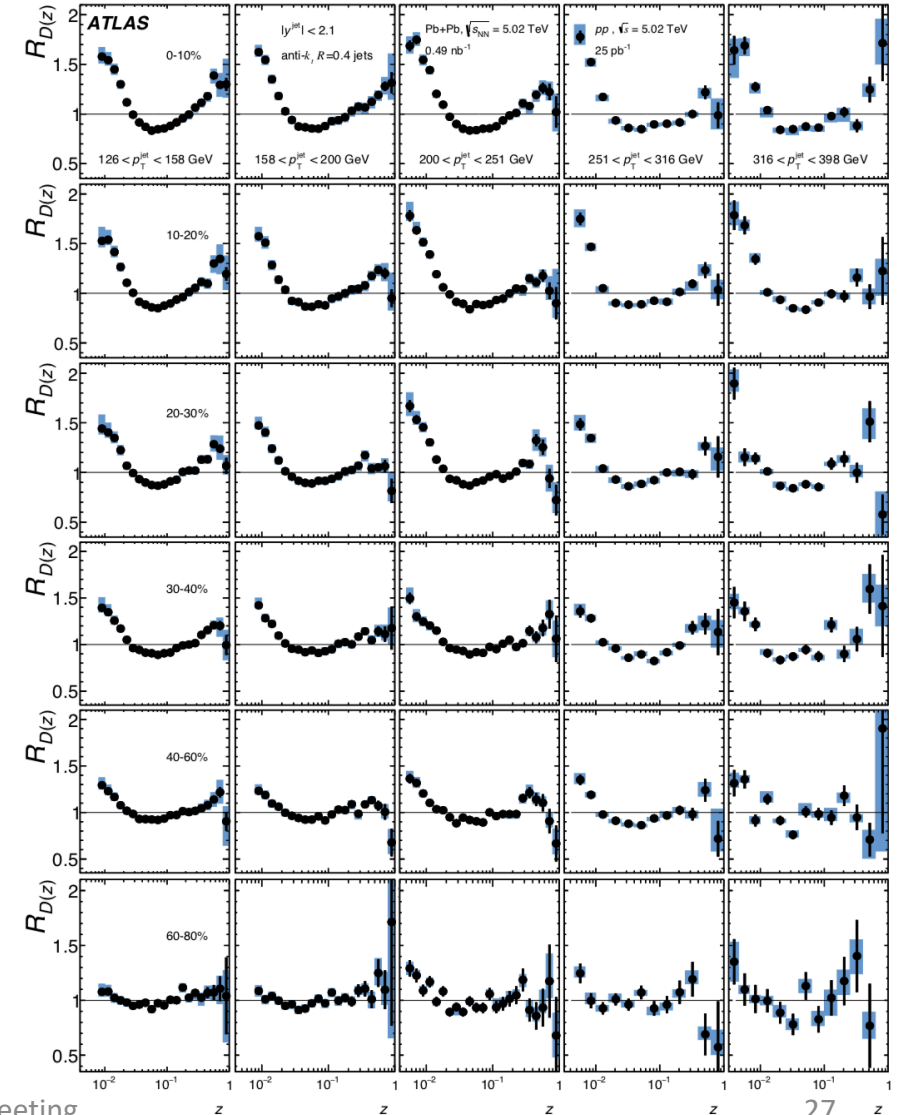
Can be measured transversely

$$D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{dn_{\text{ch}}}{dp_T}$$

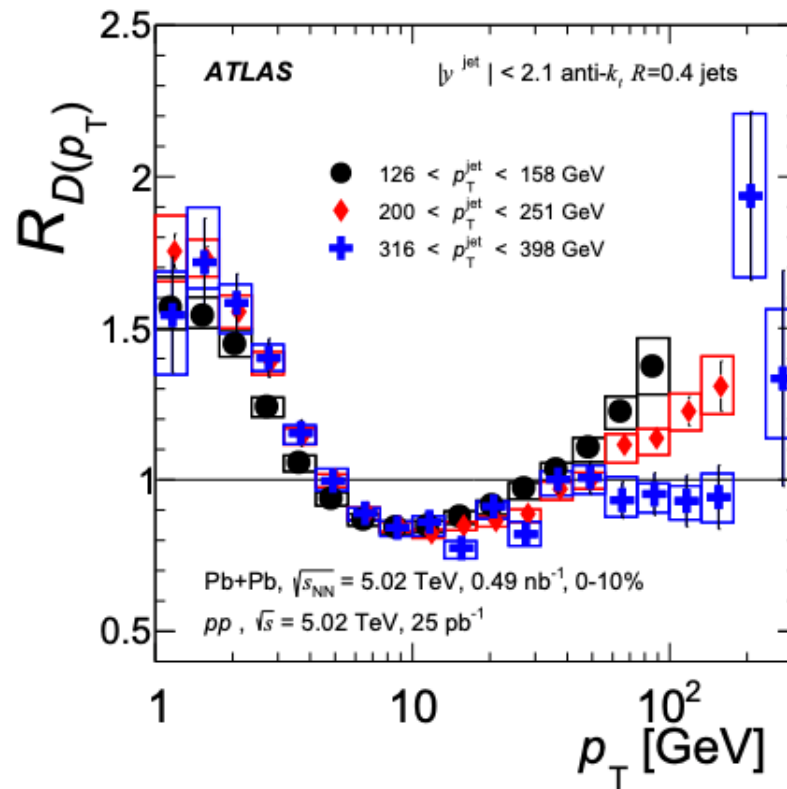
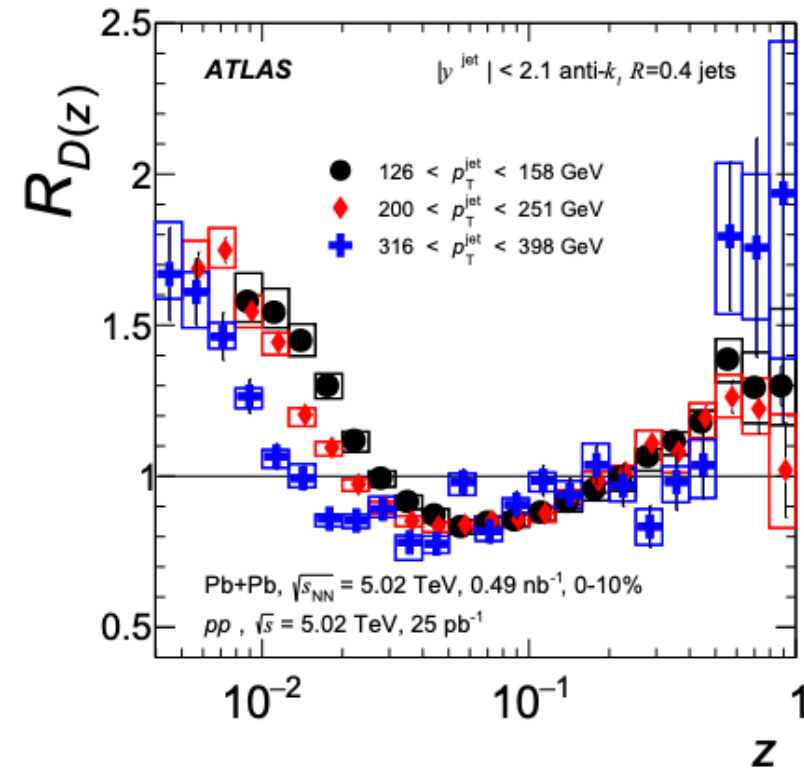
$$R_{D(p_T)} \equiv \frac{D(p_T)_{\text{PbPb}}}{D(p_T)_{pp}}$$

Fragmentation Functions

- Fragmentation Functions are modified in Pb-Pb compared to pp
- Enhancement of low p_T constituents
 - ❖ Quenching distributes the jet energy to soft particles
- Suppression of intermediate p_T constituents
- Enhancement of high p_T constituents
 - ❖ Increased quark jet fraction (less quenched)
 - ❖ Quark initiated jets have a harder fragmentation
- Modification is stronger with increasing centrality

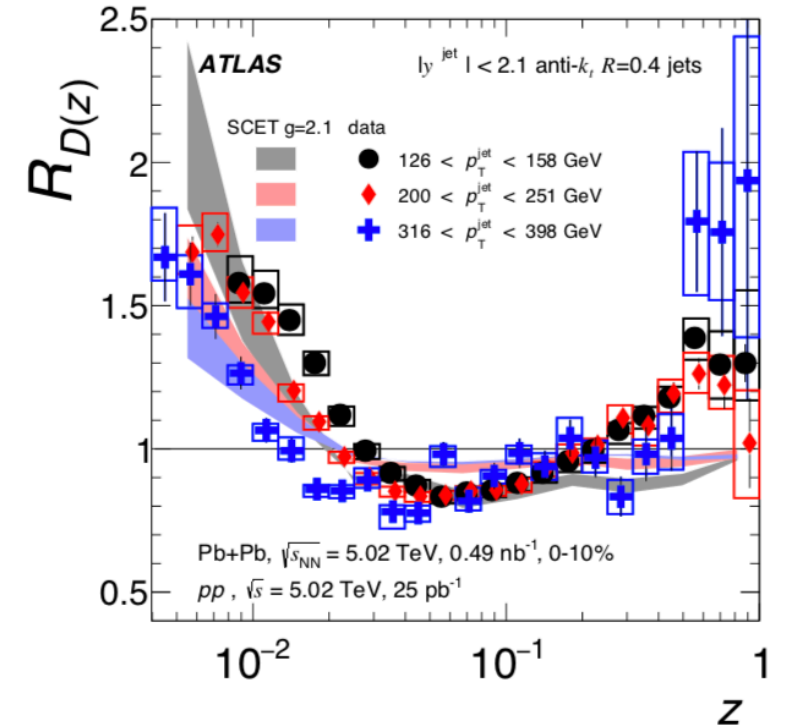
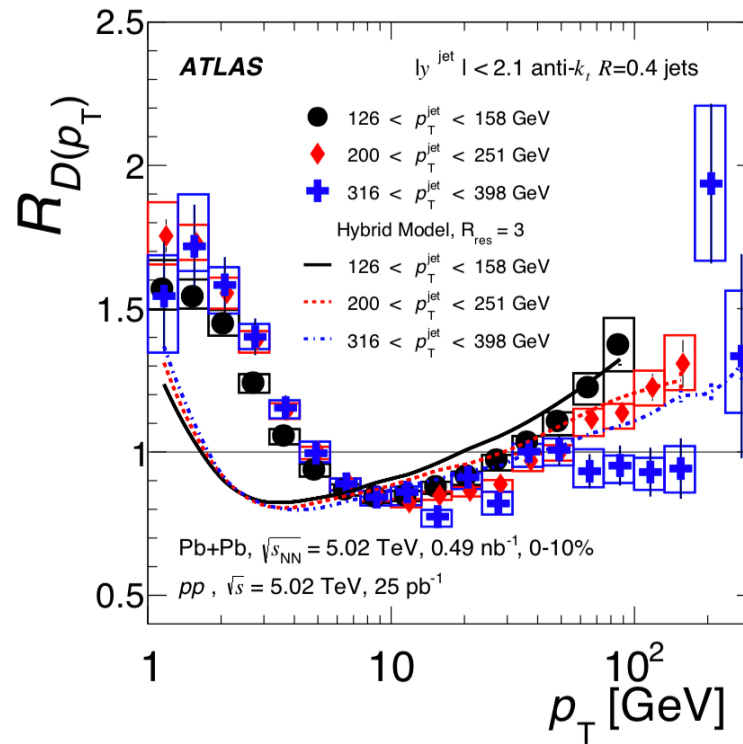
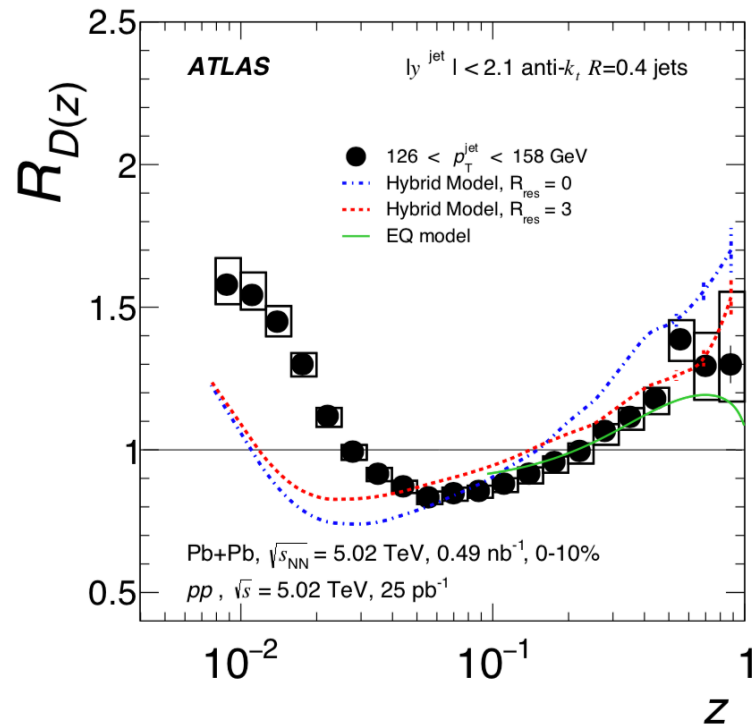


$p_{T,\text{Jet}}$ Dependence



- ❖ Stronger $p_{T,\text{Jet}}$ dependence observed for $R_{D(z)}$ compared to $R_{D(p_T)}$
- ❖ Indicates that the modification scales with z
- ❖ This is expected for fragmentation effects
- ❖ Scaling with p_T might have indicated a medium scale

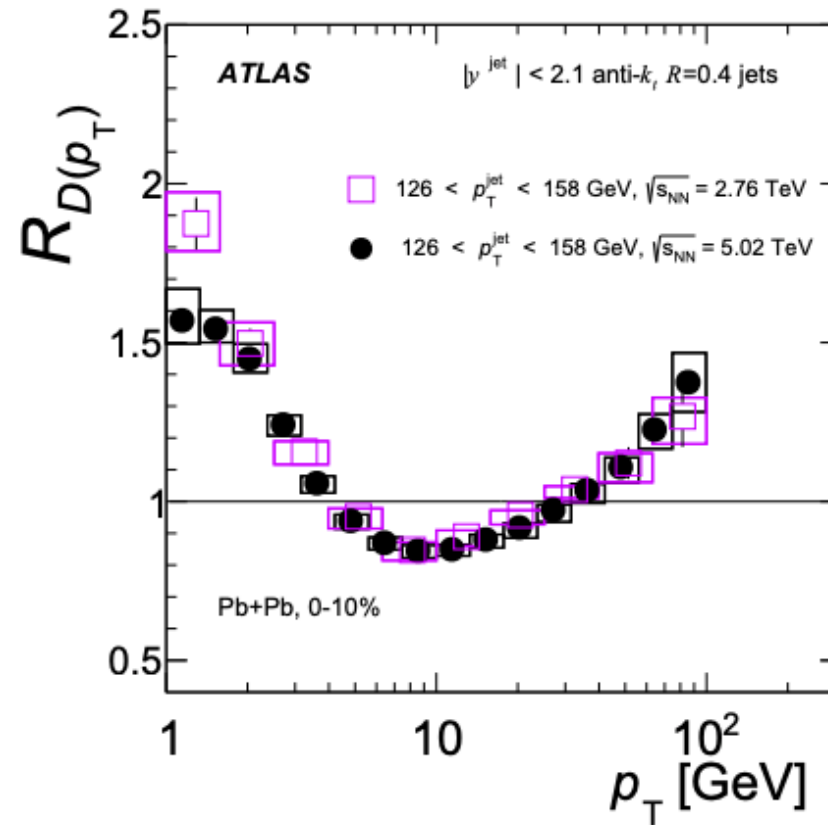
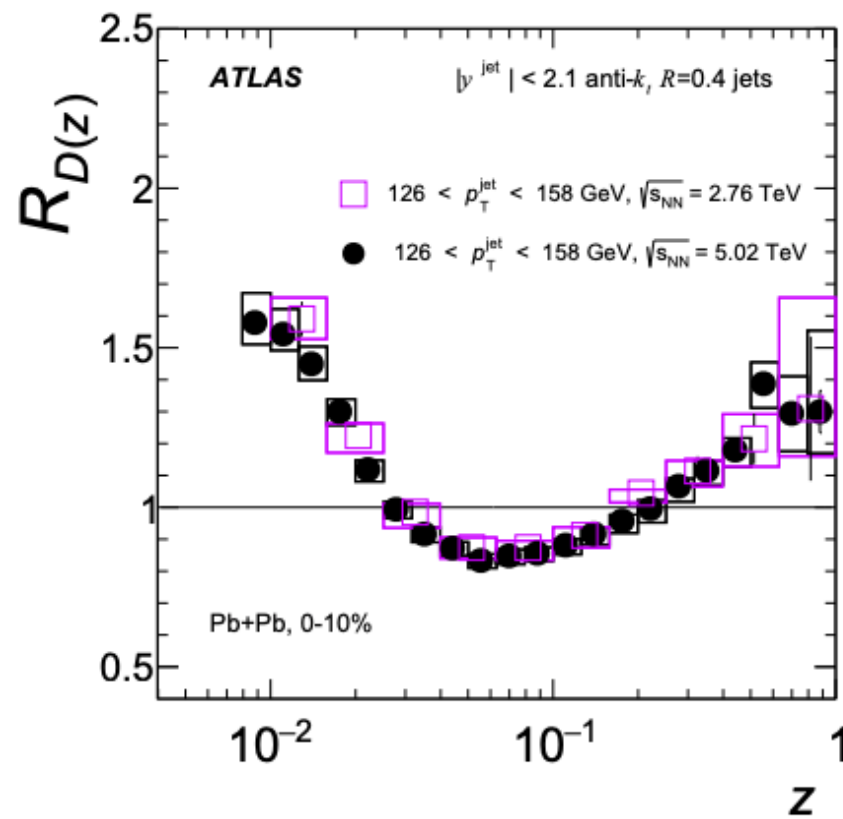
Model Comparisons



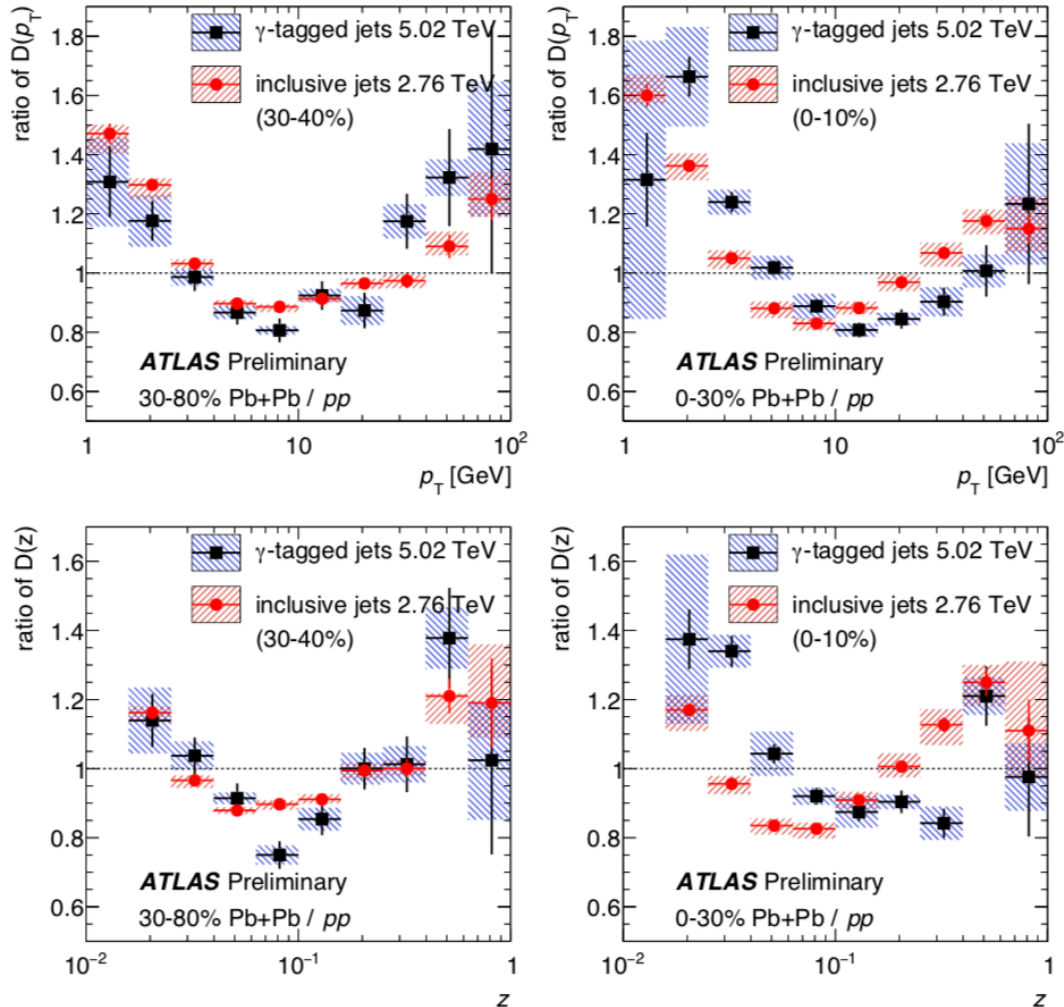
- The hybrid and EQ models describe the high and intermediate z regions well
- The SCET model successfully describes the soft and intermediate z regions

Collision Energy Dependence

No collision energy dependence observed
Allows for further comparisons between these two energies

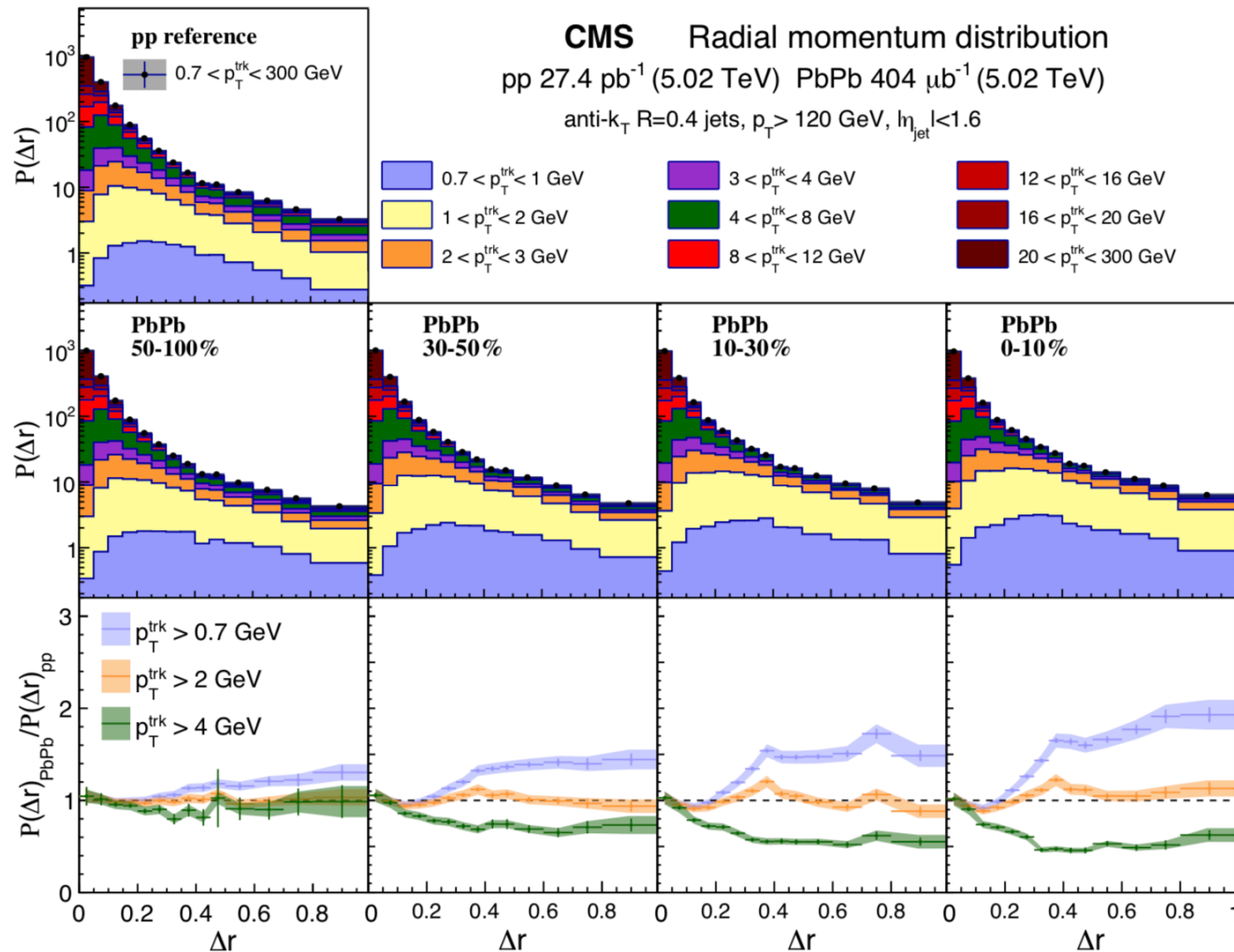


Boson Tagged Jets



- Boson tagging jets constrains the initial kinematics
- Measured jet population is less sensitive to biased quenching selection
- Reduces contribution of combinatorial jets – can go to lower $p_{T,\text{Jet}}$
- FF are qualitatively similar in inclusive and photon-tagged jets in peripheral collisions
- In central collisions the FF distributions of the photon tagged jets are shifted towards higher values
 - ❖ At the largest z and p_T values they are consistent with no enhancement
- These flavour dependent effects are in contrast to previous studies at CMS
 - ❖ Is there an interplay between flavour and kinematic selection of jets for quenching?

What is the Radial Profile of the Energy Redistribution?

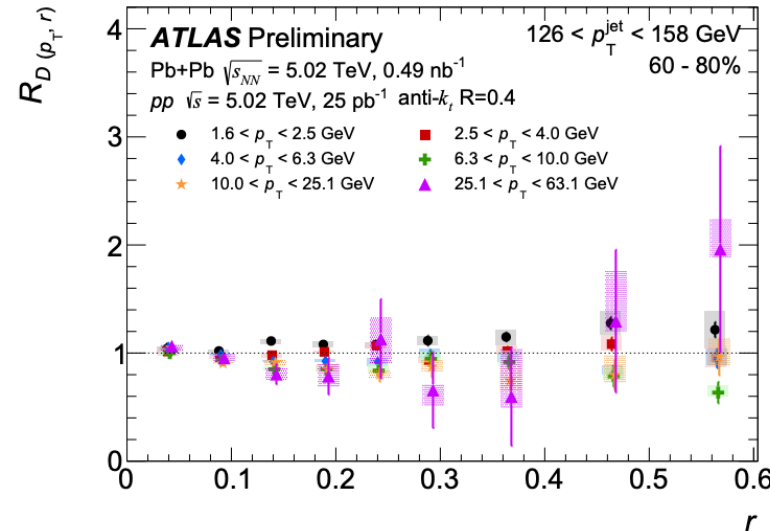
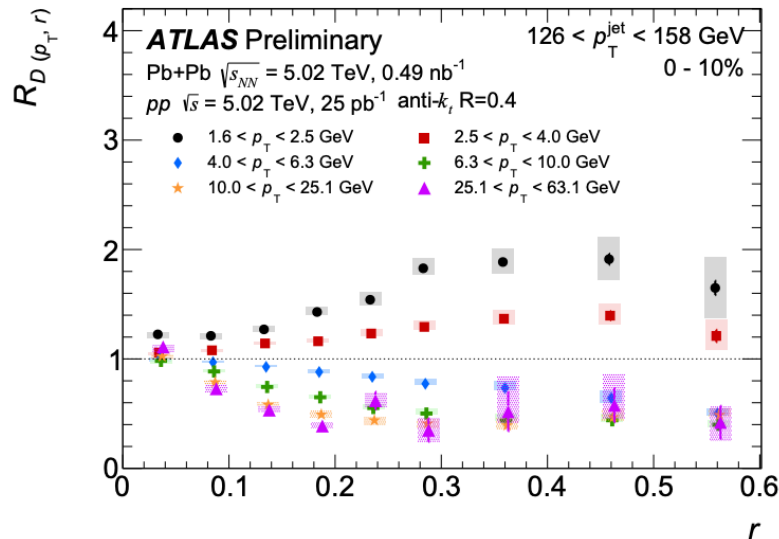


- There is a significant increase in the yield of soft particles at intermediate and large angles from the jet axis in Pb-Pb collisions.
- This magnitude of this phenomenon gets larger with increasing centrality
- This increase is compensated by a suppression of high p_T tracks at intermediate and large angles from the jet
- The excess of soft particles can be explained by quenching effects
- Hints to back-reaction from medium? Only models including a medium response can describe the data

What is the Radial Profile of the Energy Redistribution?

$$D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r} \frac{d^2 n_{\text{ch}}(r)}{dr dp_T}$$

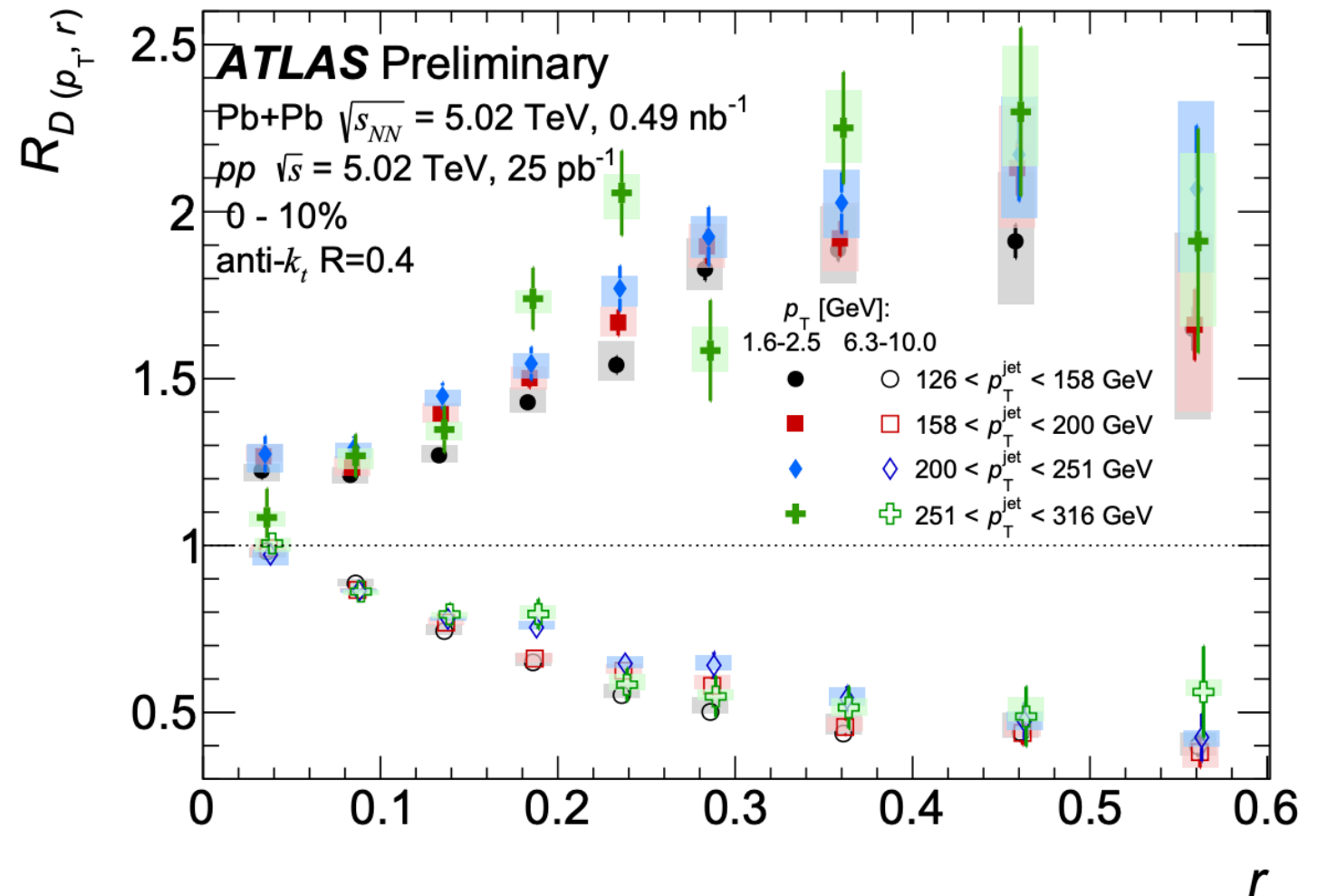
$$R_{D(p_T, r)} = \frac{D(p_T, r)_{\text{Pb+Pb}}}{D(p_T, r)_{pp}}$$



- The energy of the jet is redistributed to constituents with $p_T < 4 \text{ GeV}/c$
- The yield of these particles increases with increasing radius for $r < 0.3$ and is constant after that
- A corresponding depletion is observed for constituents with $p_T > 4 \text{ GeV}/c$
- The radial distribution of tracks is largely unmodified in peripheral Pb-Pb collisions
- These results are consistent with measured fragmentation functions and theoretical predictions – radial profile measurements are less sensitive to hadronization effects than FFs

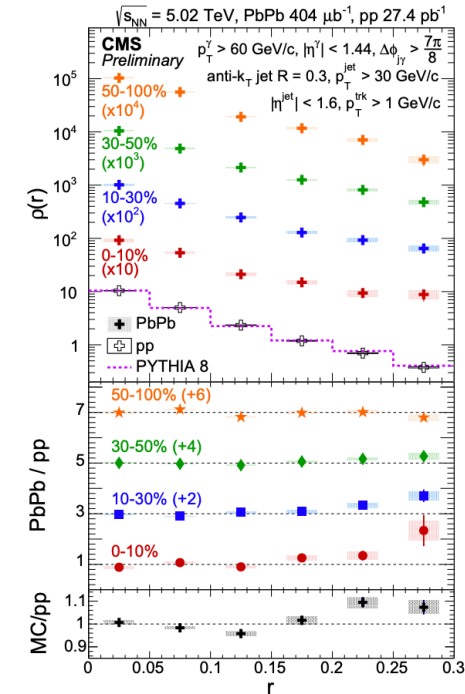
Does the Medium Respond to the Traversing Jet?

- A statistically significant trend of increasing $R_{D(p_T)}$ with increasing $p_{T, \text{Jet}}$ is observed for $0.1 < r < 0.25$
- Does this indicate a medium response to the traversing jet?
- No $p_{T, \text{Jet}}$ dependent trend is seen in the suppression of high p_T constituents

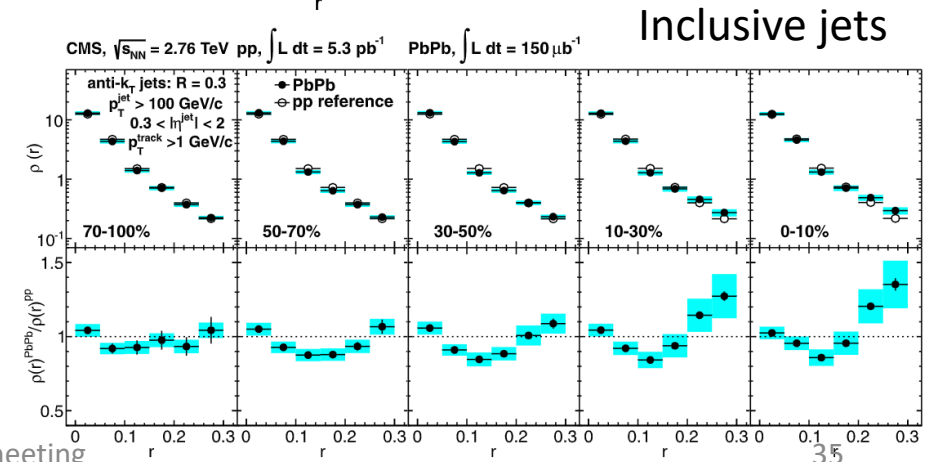


Quark vs Gluon Radial Profiles

- Gluon jets dominate the inclusive sample
- A photon tagged jet sample is used to increase the fraction of quark-initiated jets
- For both samples an enhancement of the radial profile is observed at large angles from the jet axis in Pb-Pb
- No depletion of tracks at intermediate r is observed for the quark enhanced sample – contrary to the inclusive
 - ❖ Differences between quark and gluon energy loss
 - ❖ Smaller $p_{T,\text{Jet}}$ threshold for the quark jets – increased fraction of jets with relatively larger modification



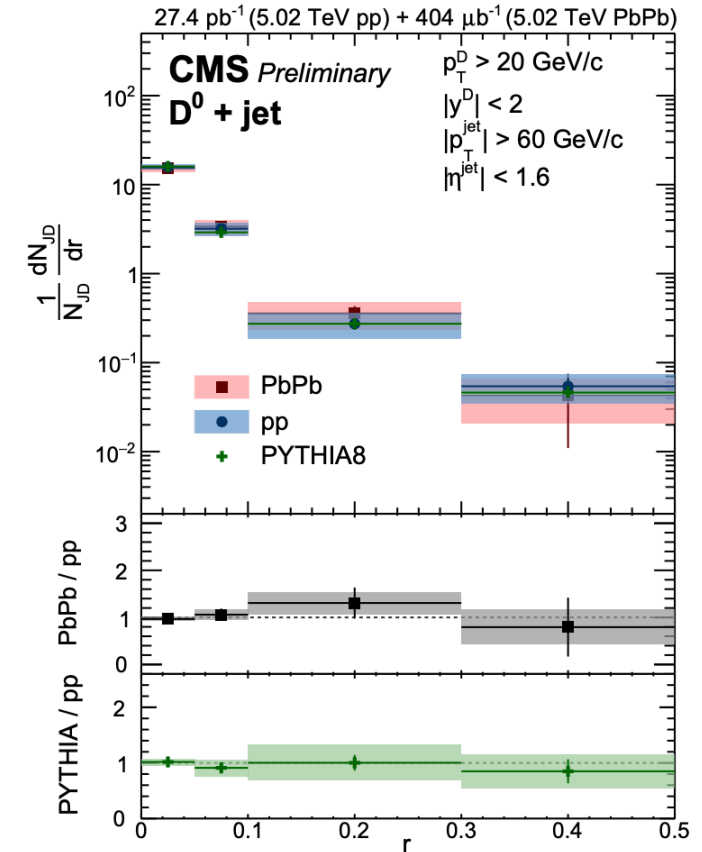
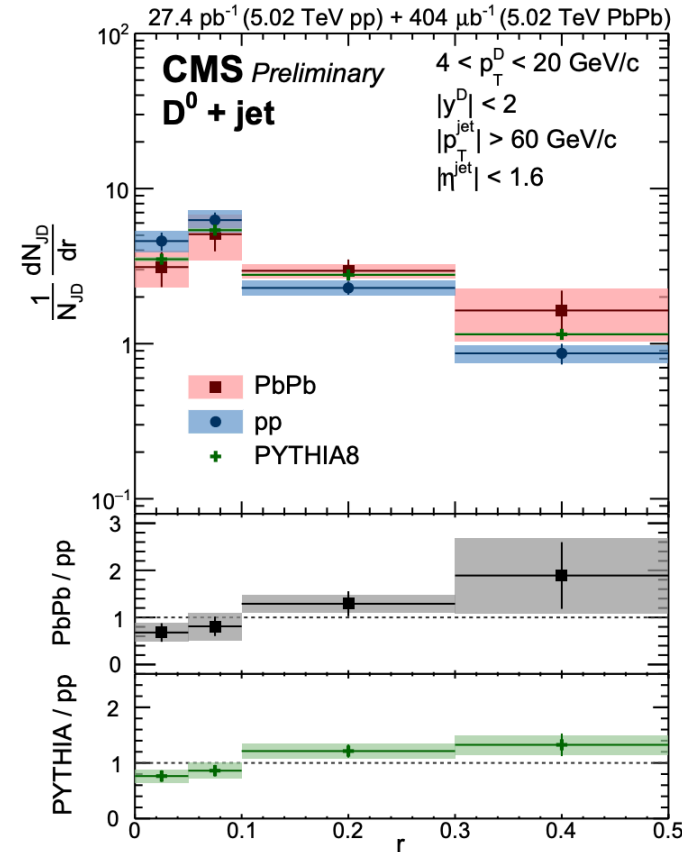
Photon tagged jets



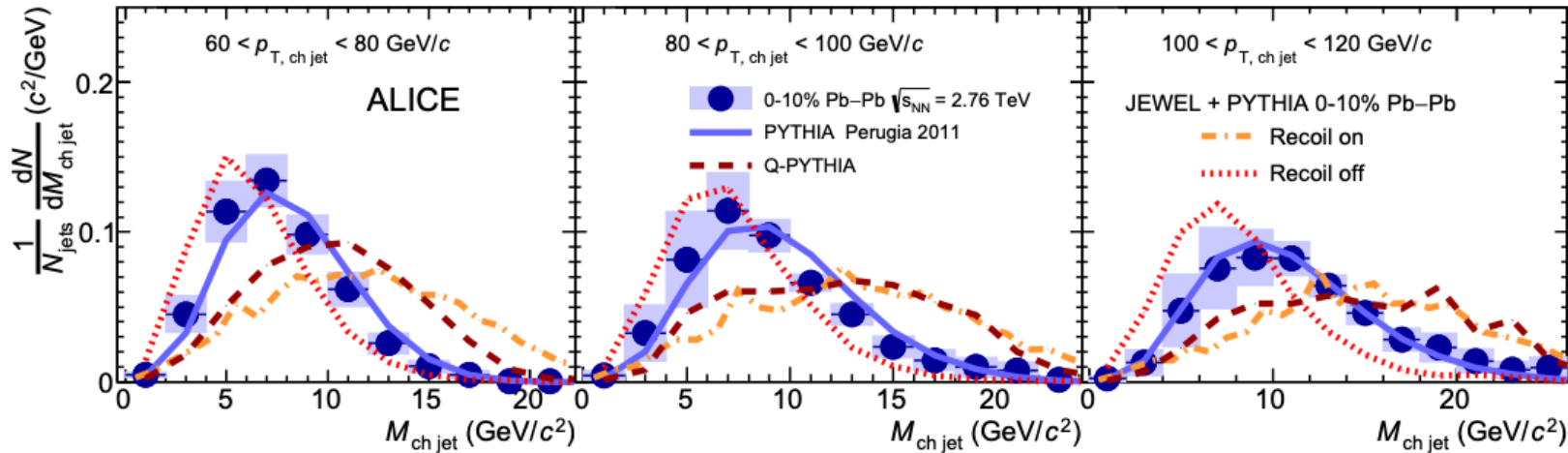
Inclusive jets

Increase the Hadron Mass

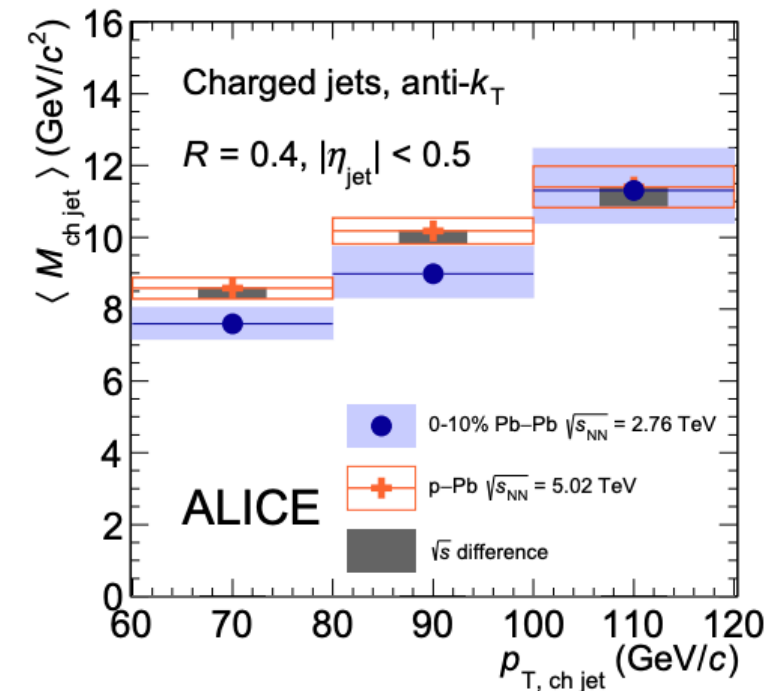
- Studying the radial profile of particles with different masses can give new insight to the mechanisms responsible for transferring soft particles to large angles
- Measuring heavy particles can constrain energy loss models and models of heavy quark diffusion through the medium
- For soft $p_{T,D}$ there is an enhancement at large radii in Pb-Pb compared to pp – The Dmeson is transported to large angles
- The radial distribution of high $p_{T,D}$ constituents is equivalent in Pb-Pb and pp



Is the Structure of the Jet Sensitive to Quenching?



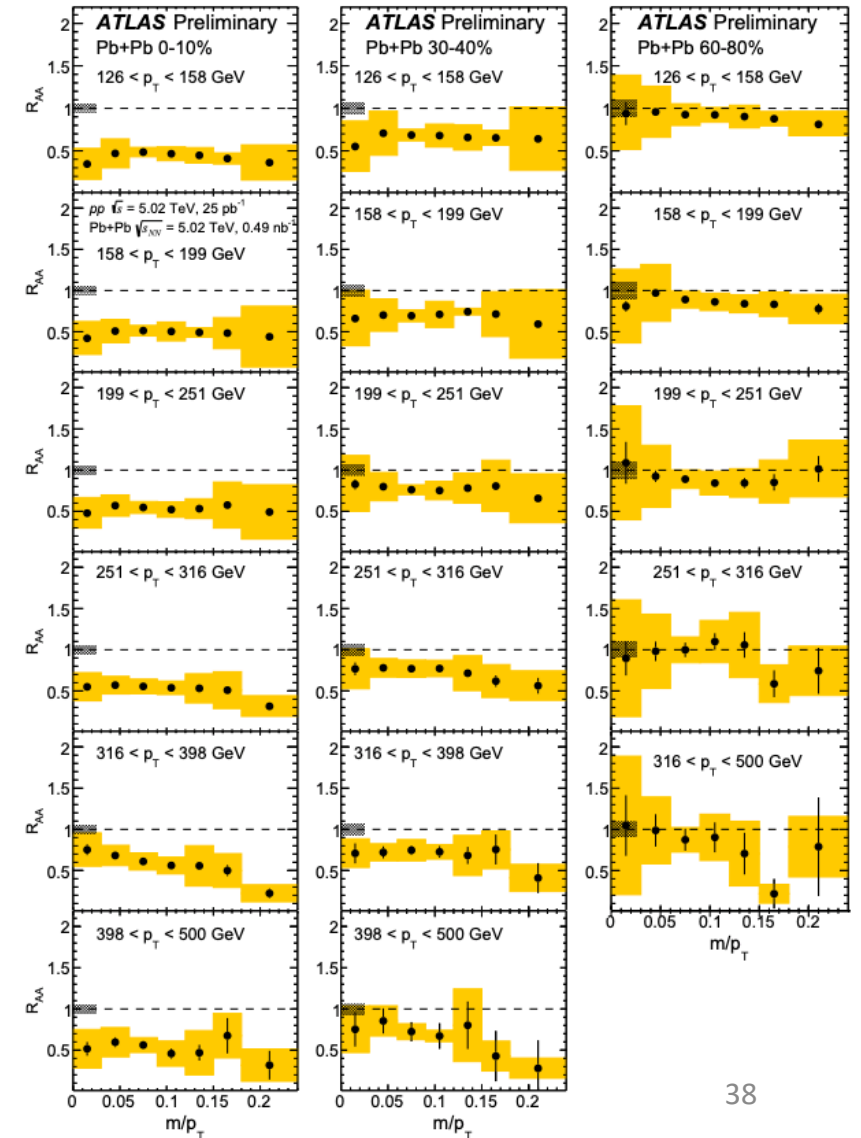
- Jet mass is sensitive to the angular distribution and multiplicity of the jet's constituents
- A depletion of the jet mass is expected in Pb-Pb due to quenching
- The jet mass in Pb-Pb is shifted to smaller values compared to p-Pb for $p_{T, \text{Jet}} < 100 \text{ GeV}/c$
- The linear increase in the mean jet mass with $p_{T, \text{Jet}}$ is expected from NLO-pQCD calculations
- The models which include quenching strongly over or underestimate the jet mass
- PYTHIA is in good agreement with the measurement in Pb-Pb



$$M = \sqrt{E^2 - p_T^2 - p_z^2}$$

Is Quenching Sensitive to the Structure of the Jet?

- Jet mass can test the resolving power of the medium
- If the jet is unresolved, energy is (coherently) lost but the substructure is vacuum like
- If the jet is resolved, (incoherent) energy loss causes a modification to the substructure
- $m/p_{T,\text{Jet}}$ is sensitive to the angular width of the jet – can be used to test coherence effects on quenching
- No dependence of the R_{AA} on $m/p_{T,\text{Jet}}$ observed
- R_{AA} is consistent with inclusive R_{AA}
- Measurements of the groomed jet mass can give clearer information about the jet core (see next talk by Yi-Chen)



Conclusions

- Jets are significantly quenched in Pb-Pb collisions at the LHC
- Quenching transports a large amount of energy outside the jet cone
- This energy is redistributed to large angles via low p_T particles
- Hints of a correlated medium response to the traversing jet?
- Boson tagging of jets provides a good unquenched reference with which to quantify quenching effects
- Opportunity to study quark vs gluon and heavy vs light quark quenching dependencies
- No strong evidence of quark flavour dependence of quenching observed yet
- No large angle in-medium deflections of the jet axis observed – need to go to lower $p_{T,\text{Jet}}$?
- Opening up the jet radius can shed more light on QGP effects – experimental tools are being developed
- Jet substructure holds the key to understanding the underlying mechanics of quenching – much more to come!

Thank You for Listening

